

**Technology Assessment and
Research Program
for
Offshore Oil Operations**

**1988 Report
OCS Study MMS 88-0057**

**United States Department of the Interior
Minerals Management Service**

*The sea never changes
and its works,
for all the talk of men,
are wrapped in mystery.*
—Joseph Conrad
"Typhoon [1902], ch. 2"

*"The sea and the wind are not our enemies. They
seldom destroy our vessels without our connivance. It
is our own folly, neglect or carelessness, that opens the
way for the attack."*

From "Yachts and Yacht Handling"
Thomas Fleming Day, 1901

The Minerals Management Service (MMS) was established by order of the Secretary of the Interior in January 1982 from components of the U.S. Geological Survey and of the Bureau of Land Management.

The MMS assesses the nature, extent, recoverability, and the value of leasable minerals on the Outer Continental Shelf and it ensures the orderly and timely inventory and development — as well as the efficient recovery — of mineral resources. It encourages use of the best available and safest technologies; provides for fair, full, and accurate returns to the Federal Treasury for produced commodities; and safeguards against fraud, waste, and abuse. The MMS ensures the protection of life, health, and the natural environment during commercial activities on leased Federal mineral lands.

The MMS is organized under a director, and activities are shared by an associate director for royalty management and an associate director for offshore minerals management.

The Branch of Technology Assessment and Research provides technology support and technical services to offshore management personnel of the MMS as they operate with industry in the open oceans and ice-covered Arctic. These Branch functions include the Oil Spill Containment and Cleanup Program, the Technology Assessment and Research Program, and a technology transfer or communications network comprised of headquarters and regional personnel.

The Technology Assessment and Research Program assesses the status of offshore technology and conducts studies which offer further assurances for safe, pollution-free operations. Studies are contracted to universities, private companies, and Government laboratories — wherever there are promising ideas and capabilities for advancing the "regulatory technologies."

Cover: Rowan Odessa jack up drills an exploratory well for
Transco Exploration Partners 15 miles offshore Texas in
Sabine Pass Block 18 in the Gulf of Mexico.
Photo by Michael Puig, courtesy Transco Exploration
Partners Ltd.

Foreword

This is the sixth biennial report of the Technology Assessment and Research (TA&R) Program. Since the inception of the program a decade ago, approximately 130 projects have been undertaken in areas of structures and pipelines, well control, oil spill containment and cleanup, and engine exhaust emission controls. These studies have yielded over 600 technical reports and papers, all of which, with the exception of proprietary studies are available to the public. These proprietary studies are projects in which the TA&R Program has shared funding with one or more companies, the reports being held proprietary to the participants or their agents for specified periods of time.

The projects and reports emanating from the TA&R Program are kept track of on a chronological basis, and by glancing through the index of projects one can quickly see how the industry's changing emphasis and its continuing development of new technologies has had a direct effect on TA&R Program planning.

On the "front burner" now are environmental concerns of oil spill response and air pollution. In addition, as a result of requirements in the recently promulgated oil and gas regulations, the Federal Government will require structural inspection information from the industry on production platforms.

The TA&R Program is devising a system to operate on the data, archive it, and perform risk analyses from it. Deep water structures, using advanced technologies not subject to peer review, are finally becoming a reality. At this writing, two such structures are being installed in the Green Canyon area of the Gulf of Mexico and two or three others are being developed.

Together with frontier area challenges for platform designers are problems always more or less attendant to oil and gas operations—the prevention and control of pollution. Readers of this report may notice that for the first time projects on oil spill containment and cleanup research and on engine emission control development are included.

If further information is desired on the projects or on other aspects of the TA&R Program please write or telephone. We shall be glad to help in any way we can. In this respect we are planning our fifth seminar for the Spring of 1989. As many know, these seminars are for the public without charge and are an opportunity for the investigators of TA&R projects to come together and to present their work. Seminars are announced in the Federal Register. Many people are on our distribution list and if others are interested we will be happy to include them.

John B. Gregory
Chief, Technology Assessment
and Research Branch

Charles E. Smith
Research Program Manager
Technology Assessment
and Research Branch

Minerals Management Service
Mail Stop 647 National Center
Reston, VA 22091
Telephone 703-648-7752

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Approximate Conversions From Metric Measures

Abbreviations	When known	Multiply by	To Find	Abbreviations
<u>Length</u>				
in	inches	* 2.5	centimeters	cm
ft	feet	30	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<u>Area</u>				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
<u>Mass</u>				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lbs)	0.9	tonnes	t
<u>Volume</u>				
fl oz	fluid ounces	30	milliliters	ml
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
<u>Temperature (exact)</u>				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
<u>Force</u>				
kip	kip-force	1000.	pounds	lbs
kip	kip-force	4448.	Newton	N
lb	pound-force	4.448	Newton	N
<u>Pressure or stress (force per area)</u>				
ksi	kip-force/square inch	6.895	Mean Pascal	MPa
lb/ft ²	pound-force/square foot	47.88	Pascal	Pa
psi	pound-force/square inch	6894.8	Pascal	Pa
<u>Bending moment or torque</u>				
in-lb	inch-pound-force	0.1130	Newton-meter	Nm
ft-lb	foot-pound-force	1.356	Newton-meter	Nm

* 1 in. = 2.54 exactly. For other exact conversions and more detailed tables, see NBS Misc. Pub. 256, Units of Weights and Measures, SD Catalog No. C13.10:286.

Approximate Conversions From Metric Measures

Abbreviations	When known	Multiply by	To Find	Abbreviations
<u>Length</u>				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.281	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
<u>Area</u>				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
<u>Mass (weight)</u>				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
<u>Volume</u>				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
<u>Temperature (exact)</u>				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
<u>Force</u>				
kg	kilogram-force	9.807	Newton	N
N	Newton	0.000225	kip-force	kip
N	Newton	0.225	pounds-force	lb
<u>Pressure or stress (force per area)</u>				
kg/m ²	kilogram-force/square meter	9.807	Pascal	Pa
N/m ²	Newton/square meter	1.000	Pascal	Pa
MPa	Mega Pascal	0.145	kip-force/square inch	ksi
Pa	Pascal	0.02089	pound-force/square foot	lb/ft ²
Pa	Pascal	0.000145	pound-force/square inch	psi
<u>Bending moment or torque</u>				
Nm	Newton-meter	8.8496	inch-pound-force	in-lb
Nm	Newton-meter	0.7375	foot-pound-force	ft-lb
Nm	Newton-meter	0.1019	meter-kilogram-force	m-k g

Introduction

ABOUT THE PROGRAM

The Technology Assessment and Research (TA&R) Program is the research branch of Minerals Management Service (MMS) offshore operations. As such it provides a formal technology base for field and headquarters personnel at a time when the oil and gas industry is moving into the deeper, rougher oceans and the ice-infested Arctic. Program studies address operational needs for the permitting of drilling and production operations (including the structural verification of production platforms), safety and pollution inspections, enforcement actions, accident investigations, and well control training requirements. In so doing, TA&R Program studies promote safety and the prevention of pollution.

The Outer Continental Shelf Lands Act, as amended in 1978, specifies "on all new drilling and production operations, and, wherever practicable, on existing operations, the use of the best available and safest technologies which the Secretary (of the Interior) determines to be economically feasible wherever failure of equipment would have a significant effect on safety, health, or the environment. . . ." To specify what MMS considers to be safe levels of operations, the Code of Federal Regulations is promulgated. A number of program directives have been developed to define and interpret acceptable levels of performance that must be met by the offshore petroleum industry. Among these measures are, for example, Notice to Lessees (NTL), the Well-Control Certification Program, and the Platform Verification Program.

The Platform Verification Program reviews the design, fabrication, and installation of new production platforms, and many TA&R Program studies address its needs. These needs will, no doubt, increase in the years ahead to include technologies for periodic in-service inspection because of the newly revised Code of Federal Regulations. This new code requires information on what industry structural inspections have been made, what has been found, repaired, and what is the structural condition of the platform.

As mentioned above, the TA&R Program addresses the needs of MMS operations personnel; they are the users of the research. To assure good communications between TA&R and the operations personnel, who operate from regional offices around the periphery of the United States, a technology transfer network is established. The network consists of working groups located in regional offices and in headquarters (Operations Technology Assessment Committees, OTACS) which discuss operational problems and relevant technologies. Where deemed appropriate, regulatory recommendations are made to MMS management. The OTACS provide a forum for operations staffs, TA&R Program managers and investigators to discuss research projects in a timely manner.

TECHNOLOGY ASSESSMENT AND RESEARCH

The projects of the TA&R Program are divided into three categories: well control or the prevention of blowouts, structures and pipeline behavior and inspection, and the prevention of ocean and air pollution.

WELL CONTROL

At the heart of safe offshore operations is well control—the ability to drill and produce oil and gas without sustaining blowouts. If such catastrophes do occur, the blowing well must be brought under control to minimize possible loss of life and property and pollution of the ocean. Normal well control operations and blowout situations can be reduced to practical problems in fluid mechanics. These situations can be solved by understanding all the variables of the system and by using effective equipment, knowledgeable procedures and personnel. If the geophysics of the rock and sediment and the behavior of the various fluids in the well were better known, and if the driller had immediate knowledge of what was happening downhole, appropriate and timely decisions could be made to control potential blowout conditions.

Drillers must not only keep the fluid pressure dynamically balanced during drilling operations, but they must also determine if some part of the structure has failed—whether it be casing, cementing, or formation. Immediate knowledge of these failures could alert drillers to take effective countermeasures.

At Louisiana State University (LSU) two major aspects of well control are being investigated: well control assisted by on-line bottom-hole pressure measurements while drilling (MWD), and diverter operations. The MWD is a technique developed a decade ago to provide bore-hole directional information while drilling. The usual technique is to transmit coded pressure pulses through the drilling fluid. The pulsing devices currently in use are mechanical and cannot pulse quickly enough to provide safety-related data. In deep-water drilling operations, the ability to have on-line (while drilling) safety information (bottom hole pressure) would greatly enhance drilling safety. At present, drillers read surface gauges attached to very long flow lines, which extend from the drill floor to the ocean bottom hundreds or thousands of feet below. These flow lines add much fluid flow friction, and it is very difficult to control bottom hole pressures in a well under transient conditions. By using a pulser valve, which operates on fluidic principles (the fluiddynamic analog of a mechanical valve), the data rate can be greatly increased and can provide bottom-hole safety information, on line, to a driller. These data can be processed through a computer which automatically operates the surface choke, thus controlling the circulation in the well in a timely manner. The LSU has experimented at full scale with such techniques. In particular, the fluidic pulser used is an experimental device developed by the Harry Diamond Laboratories of the U.S. Army under sponsorship of the TA&R Program.

Nothing is really proven to be system worthy until it is operated under realistic conditions. Presently, LSU is devising a simulated full-scale physical model with which to test the various elements of the MWD well control system. Elements of this system were discussed in the previous Technology Assessment and Research Program Report, 1986 Report, OCS Study 86-0083.

Diverter operations have also been under analysis at LSU. These large-pipe systems, 6 inches or more in diameter, divert shallow gas away from drilling platforms before blowout preventers are set in place. Operational experience with diverters, in general, has been less than satisfactory, and consequently, under TA&R sponsorship, LSU has been analyzing and modeling diverter design and operations. As a result of LSU's research it appears that large-scale improvements can be had only by resorting to innovative concepts for gas diversion. For example, the underwater shunting of gas may prove safer than the present above-deck-method.

As an adjunct to well control, experimental studies are being conducted by the National Bureau of Standards to determine the feasibility of suppressing blowout fires by entraining water sprays in the flames. Thermodynamic analyses are revealing that, with very little cost to operators, piping systems can be rigged to extinguish or, if desired, reduce the temperature of blowout fires. Research has determined that water requirements are minimal, though nozzle placement is critical. It is not presently known what the degree of flame cooling, compared to oxygen starvation, is responsible for extinguishment. Also, and perhaps most importantly, the effect of structural interference in the flame column needs to be quantified. Thus far, research has concentrated on gas flames but is continuing with the study of mixtures of oil and gas.

Blowout fire suppression offers a new and vital means for permitting personnel time to escape from a rig or platform and to save the platform from destruction. In addition, it may prove to be a useful method for preventing oil pollution if suppression measures allow the flames to persist but at relatively low temperatures, thus permitting reoccupation of the rig for well recontrol.

STRUCTURES AND PIPELINES

The TA&R Program continues to analyze the technological problems encountered in the design, fabrication, and inspection of frontier area structures—installations for the continental slopes, and for the ice-infested Arctic. In the Arctic the predominant structural problems of designing for various forms of ice loadings are gradually being worked out, but it will be at least several years before engineers will be able to design with confidence. It is a two-pronged problem—knowing the mechanical properties of the ice and designing a structure to withstand damage and movement.

For the past 5 years, the TA&R Program has participated with the industry in coring, testing and analyzing the engineering properties of ridge ice. Results are quite illusive, multi-year sea ice having a very inhomogenous structure. Presently, emphasis is upon basic research into the fundamental proc-

esses by which fresh and saltwater ice are formed and behave. For the MMS, this research is being accomplished at Dartmouth College under the sponsorship of a consortium of private companies and Government Agencies. But knowing the physical properties of ice are not enough, and at MIT work is in progress to determine the mechanisms by which ice impinges a structure and fails. Lastly, the total force of the ice driven by wind stress and ocean currents has to be determined, and over the past 7 years, the MMS, together with the Cold Regions Research and Engineering Laboratory, have cooperated with oil industry operators in the Beaufort Sea in the use of ice stress gauges around installations.

Ice can also be used as a material to construct an island for drilling or as a berm to protect structures. Spray ice, which is made from sea water sprayed into the air, has successfully been used in the Arctic as a material for protective berms and islands for exploratory drilling. The enormous mass of these spray ice structures can absorb the large loads created by the moving ice floes and they can be constructed at a reasonable cost.

At this writing, all eyes are upon the events leading up to the installation of two new technology structures for the very deepwaters of the Green Canyon area of the Gulf of Mexico, a quickly sloping oil-rich site 150 miles southwest of New Orleans. One platform, the Conoco Tension Leg Well Platform (TLWP), is to be installed in 1550 feet of water, a deepwater record for production platforms. The platform will consist of a buoyant hull section up to which hydrocarbon production risers will be run. The platform will be pulled down to suppress wave action by heavily loaded tensioned legs or tendons, as they are usually called. The tendons, in turn, will pull against a seabed foundation held in place with tensioned pilings.

The second platform is Placid Oil Company's Floating Production System (FPS). This installation was installed in even deeper depths—1750 feet. The hull of the FPS is a large semisubmersible drilling rig modified with pontoons to provide increased buoyancy for supporting production equipment. Instead of tendons the FPS maintains position with a taut wire rope multipoint mooring system. Whereas the hydrocarbon risers of the TLWP individually reach up through the water column to the hull, on the FPS flow lines and risers are contained in a single 7-foot overall diameter package which has buoyant sheathing to partially support its weight. Both of these platforms and at least several modifications of them—which might be envisioned, are being analyzed in considerable detail by the industry and the MMS. Whereas it is logical to install these new technology platforms at this time, it must be remembered that some structural aspects have little or no comparable operational experience to guide designers. Therefore, designs need to be closely verified by MMS and in-service performance rigorously monitored. These kinds of problems, discussed herein, result from the application of materials and the behavior of the elements in a complex dynamic system. For example, existing platforms, with the exception of the Conoco Tension Leg Platform, installed in the North Sea, have risers which are secured at relatively short intervals between the foundation and deck. But TLP's and FPS's do not have the structure to afford such bracing. Therefore the risers, unsupported through their complete length, are subjected to the vibratory motions of ocean current induced excitation known as strumming, and also to platform excursions from waves, winds, and current.

Other foreseen problems pertain to the future use of high-strength steels for members such as tendons. These steels will have to be used in certain future deepwater installations where platform weight is an overriding consideration. The steels will have to be carefully selected, welded, inspected, and protected from the ocean environment. Trade-offs will have to be made by designers between toughness and tensile strength to avoid, in particular, two modes of catastrophic failure—stress corrosion cracking and corrosion fatigue.

Pilings in tension are another area of concern. Much research has been accomplished by Conoco on both driven piles and on drilled and grouted piles, and operational experience will be valuable in the determination of the actual state of the art. For example, if a pile is inserted into a predrilled hole, and grouted in place, how is the holding capacity in tension and integrity of the pile assessed?

Other problems, such as designing for seismic loadings on platforms sited off California, and in future years off the Aleutian chain (to mention the notorious earthquake-prone areas), need to be worked out as industry operations move into deeper and more hostile waters using less structurally redundant and

lighter platforms. Both the industry and the MMS are cooperating in the measurement of these loadings and the responses of platforms to them. These measurements cannot properly be extrapolated from onshore seismic measurements but must take into account the ocean sediments and the incident and reflected shock waves transmitted through them and through the water column.

As mentioned earlier in this chapter, the MMS is, for the first time, requiring the industry to report annually the results of its underwater inspections of platforms. This information, properly analyzed, will afford much improved insight into service experience with, not only the newer platforms, but, as well, the many aging Gulf of Mexico structures. These data will be important to the MMS as it supervises industry operations to assure that they are safe. In this respect, industry and the MMS are participating jointly in studies pertaining to risk and reliability of platforms whether new, old, or damaged.

OIL SPILL CONTAINMENT AND CLEANUP

During the past 2 years, primarily in conjunction with a cooperative research program with the Department of the Environment, Canada, strides have been made in quantifying the ability to contain and clean up oil spilled in the open ocean. Two methods of approach have been used: the examination of fundamental principles and at-sea experimentation.

In response to an oil spill, a number of factors determine operational effectiveness. The oil spill has to be reported expeditiously and accurately. A properly equipped response team trained in the use of equipment applicable to the spill environment and ready for deployment on suitable response vessels has to arrive on scene quickly. Only after all of these factors are in order is the very difficult operation of clean up feasible. In addition, all of the measures appropriate for the cleanup operation need to have been approved by the Government for usage. (For example, the burning of oil or the use of chemicals are controversial and are in many areas not permitted.)

The MMS program is addressing the three aspects of containment and cleanup: mechanical, burning the oil on the surface of the ocean, and using additives to disperse the oil into the sea or to assist in its retrieval.

The effectiveness and the proper application of dispersants is controversial. Advocates maintain they are useful if properly applied, others consider them to be marginally effective. The matter has been referred by the MMS to the Marine Board of the National Academy of Engineering for analysis. The findings probably will be available by the date of this printing.

What appears to be most promising as a spill response technique, especially for confined seas such as broken ice fields, is the burning of oil on the ocean surface, whether the oil is fresh or weathered. Emulsified oil does not burn well. The National Bureau of Standards has been conducting tests to determine the products of combustion and residues of burned oil, and preliminary results indicate that approximately 90 percent of the oil can be burned. Tests need to be run at large-scale and in the open-ocean to verify laboratory analyses, and these are being planned in conjunction with Environment Canada.

Mechanical means for recovery of spilled oil have received the preponderance of attention over the past score of years. With certain exceptions, such as flameproof, fireproof booms, mechanical recovery equipment are developed to a mature stage. However, rating the performance of boom-skimmer systems has been a matter of manufacturer claims. Recently, through a joint MMS-Environment Canada-Canadian Coast Guard at-sea exercise, instrumented boom tests were performed, using spilled oil to validate criteria for prescribing standardized nonoil-spill procedures for evaluating all open-ocean booms. These offshore tests revealed certain shortcomings in rough water boom-tow procedures and, in addition, revealed that certain oil additives enhanced the ability to suck the oil from the pocket of the boom, thus greatly improving operational effectiveness. The non-polluting test procedures were validated.

Another finding during this exercise is that containment booms can be operated effectively by towing downwind in conditions far exceeding the maximum sea states which have caused failure in booms operated in the normal upwind mode. One other aspect of the offshore tests was the satisfactory use of "detuned" shipboard navigational radar to locate oil slicks up to distances of 12 miles in a range of sea states. Further experiments and analyses are planned.

ENGINE EXHAUST EMISSION CONTROL

Combustion engine exhausts yield several pollutants which effect health: CO, CO₂, NO, NO₂, SO₂, and particulates. A variety of these pollutants can be reduced by means of altering combustion cycles, modifying fuels, and treating exhaust gases. The procedure used depends upon the circumstances. In coal mines, for example, the particles, which are almost entirely respirable, have the ability to absorb other potentially carcinogenic hydrocarbons and gases such as SO₂ and NO₂, acids such as H₂SO₄ and HNO₃. The basic objective, therefore in emissions control in coal mines (where diesel engines are used to produce mechanical energy for mining) is to reduce particulates, an objective accomplished by operating engines at maximum efficiency and by "scrubbing" engine exhaust gasses.

Operations on the Outer Continental Shelf also use diesels as prime movers, especially for drilling rigs and boats. The production platforms employ gas turbines, which, to a large extent, are fueled with natural gas. Of primary concern to the along-shore population are the visible and irritating effects of smog produced by these engines and from automobiles, shore power plants, etc. Though particulates are of concern, the nitrogen oxides (NO_x) are considered by air quality control stratifies as the primary offenders. Of the nitrogen oxides, NO₂ is the most dangerous. It is a brownish haze in color and reacts in the atmosphere to produce ozone. NO₂ irritates the eyes and lungs.

As combustion temperatures increase, NO_x production increases as well. To comply with the requirements of civil authorities, offshore operators have used techniques such as water injection with fuel to lower the temperature. But though this method is relatively simple it derates engine thermal efficiencies, reduces engine life, increases exhaust soot and is only of limited effectiveness in reducing NO_x. Other techniques are available and are proving to be significantly more efficient. These methods modify the combustion process and/or treat combustion products either catalytically, chemically, or both. Several methods appear fruitful for analysis and possible demonstration on the OCS. Such an analysis requires the scrutiny of about nine criteria such as process efficiency, first cost and operational costs, safety, and environmental effects. When the analysis is complete, a program needs to be devised to develop candidate techniques to a level where they can be evaluated in offshore demonstration projects on gas turbine and diesel engines.

The TA&R Program is currently working through Arthur D. Little, Inc., to perform such an analysis and to devise a plan. In addition, it is participating with the U.S. Department of Energy to investigate a new exhaust treatment technique known as Raprenox which does not require a catalyst and uses a nontoxic chemical agent.

As previously stated, the TA&R Program is examining the technologies applicable to MMS offshore operations through a contract research program. The application of the vast scientific and technical interdisciplinary knowledge, which exists in the universities, Federal laboratories, and private companies is essential to the prudent regulation of an industry that is constantly expanding into new hostile environments.

The TA&R Program encourages innovation and creativity which can be accomplished only by attracting talented scientists and engineers who are dedicated to the furtherance of science and technology. Good science and technology can only be accomplished when several variables converge; a talented investigator doing his own research (which happens to coincide with MMS needs), available resources, and proper time frames. The TA&R task is to "beat the bushes" for innovative people. Scientists and engineers learn of MMS interests through Program announcements in the Federal Register, Program reports, and by attending TA&R Program seminars.

Experimental Study of Diverter Systems Used in Offshore Drilling Operations

Principal Investigator: Dr. Adam T. Bourgoyne, Jr.
Petroleum Engineering Department
Louisiana State University
Baton Rouge, Louisiana 70803

Objectives: To determine improved design criteria for blowout prevention systems used to handle flow from shallow gas sands during offshore drilling operations.

Blowouts are among the most dangerous hazards of offshore oil and gas exploration. When a well threatens to blowout, the quick use of properly designed blowout prevention equipment is necessary to avoid harm of personnel, equipment, and the environment, and to avoid loss of valuable natural resources. Well control is especially difficult when a threatened blowout situation occurs at a shallow depth, prior to setting surface casing in the well. Under these conditions, normal well control operations cannot always be employed. If the well is closed at the surface using blowout preventers, hydraulic

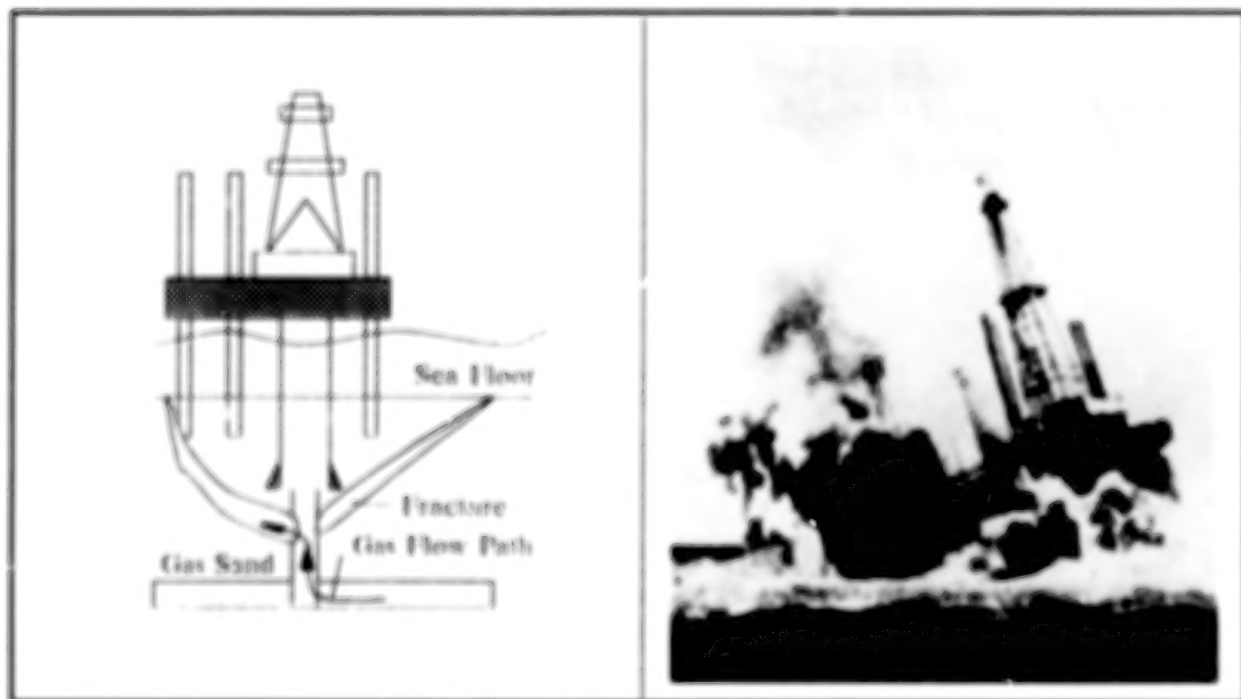


Figure 1 — Example Blowout Illustrating Need for Diverter System.

fracturing is likely to occur in an exposed shallow formation due to the build-up of pressure in the well. If one or more fractures reach the surface, the resulting flow can destroy the foundations of a bottom supported structure (Figure 1).

When drilling from a bottom supported structure, the best available procedure for handling a threatened blowout from a shallow gas formation is to divert the gas flow away from the structure and drilling personnel. This requires the use of a diverter system that is large enough to prevent a pressure build-up in the well above the fracture pressure of the weakest formation that is exposed to the wellbore pressure. The essential elements of a diverter system include (1) a vent line for conducting the flow away from the structure, (2) a means for closing the well annulus above the vent line during diverter operations, and (3) a means for closing the vent line during normal drilling operations.

The sequence of events occurring when a shallow gas flow is encountered are illustrated in Figure 2. When the driller recognizes that the well has begun to flow, the diverter system is actuated (2b). This simultaneously causes the vent line to open and the annular diverter head to close. If the well plan calls for a dynamic well control method to be attempted with the rig pumps, the driller may continue to pump drilling fluid at the maximum possible rate in an attempt to regain control. As drilling fluid is displaced

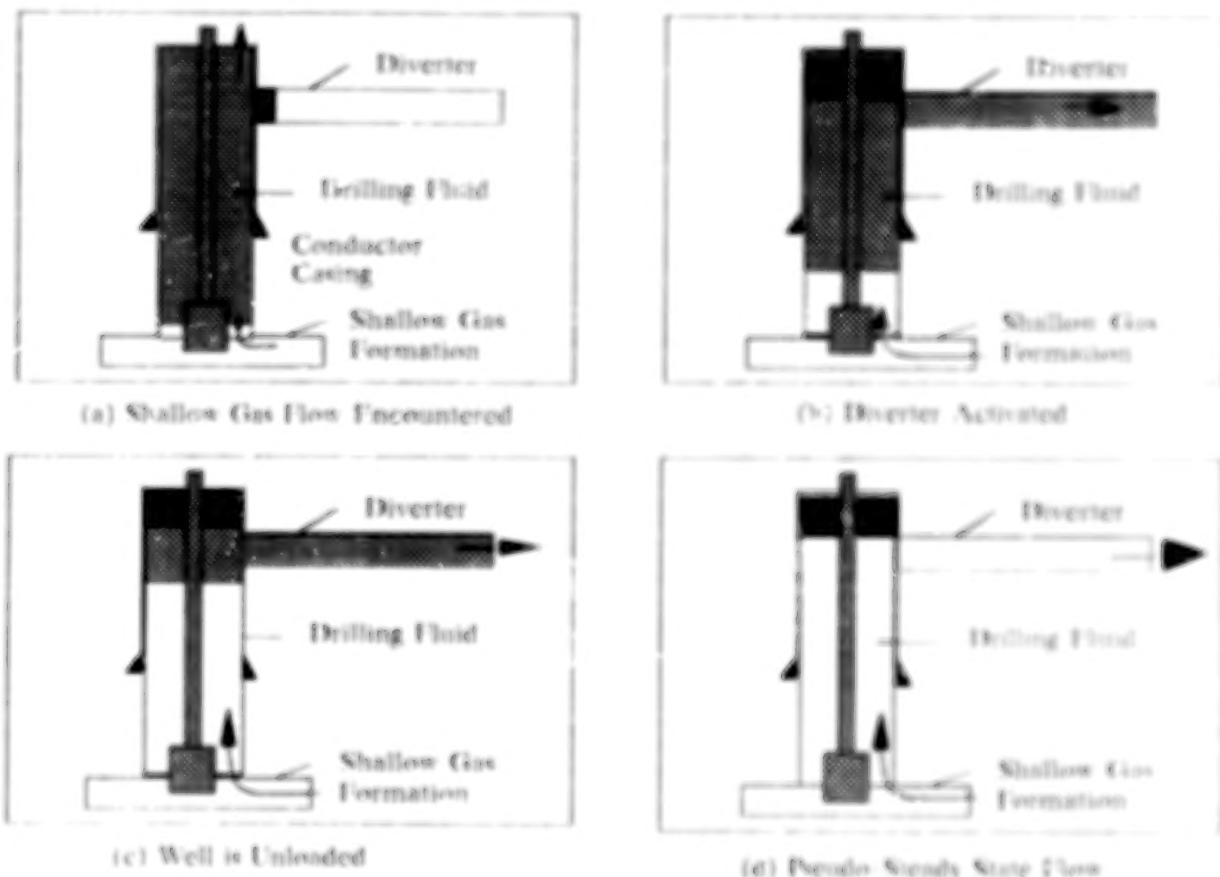


Figure 2 — Sequence of Events During Diverter Operations.

from the well, the rate of gas flow into the well increases due to the loss in bottom-hole pressure (2c). After the well is unloaded of drilling fluid, a semi-steady state condition is reached (2d) in which formation gas, water, and sand are flowing through the vent line. The loss of drilling fluid from the wellbore will usually result in an unstable borehole wall that will eventually cave in and form a plug that stops the flow. However, in some cases it has been necessary to drill a relief well to stop the flow.

Although conceptually simple, the design, maintenance, and operation of an effective diverter system for the various types of drilling vessels is a difficult problem. On most offshore drilling structures, the diverter system is designed after the rig is built, complicating the routing of the vent lines and resulting in the need for bends in the piping. Past experience has shown that when a situation calling for the use of a diverter arises, failure in the diverter system often occurs. This high failure rate indicates the need for developing improved design criteria for these systems. A review of field experiences with diverter systems indicates that failures generally result from (1) higher pressures than expected, (2) erosion caused by produced sand, (3) poor anchoring of piping and other components, (4) valve failures, and (5) human error. The trend to larger pipe sizes in modern diverter systems has reduced the risk of plugging, although settling of barite from the drilling fluid in low sections of diverters with uphill pipe runs can still present potential hazards.

In order to improve the accuracy at which the various loads imposed on a diverter system could be predicted, a number of experiments were performed and fall into the following categories:

1. Measurement of flowing well pressures under unsteady state conditions occurring while drilling

- fluid is being displaced from the wellbore (Figure 2c).
2. Measurement of sonic exit pressures and flowing pressure gradients in the diverter line as a function of flow rate for steady state multiphase flow of gas/liquid mixtures (Figure 2d).

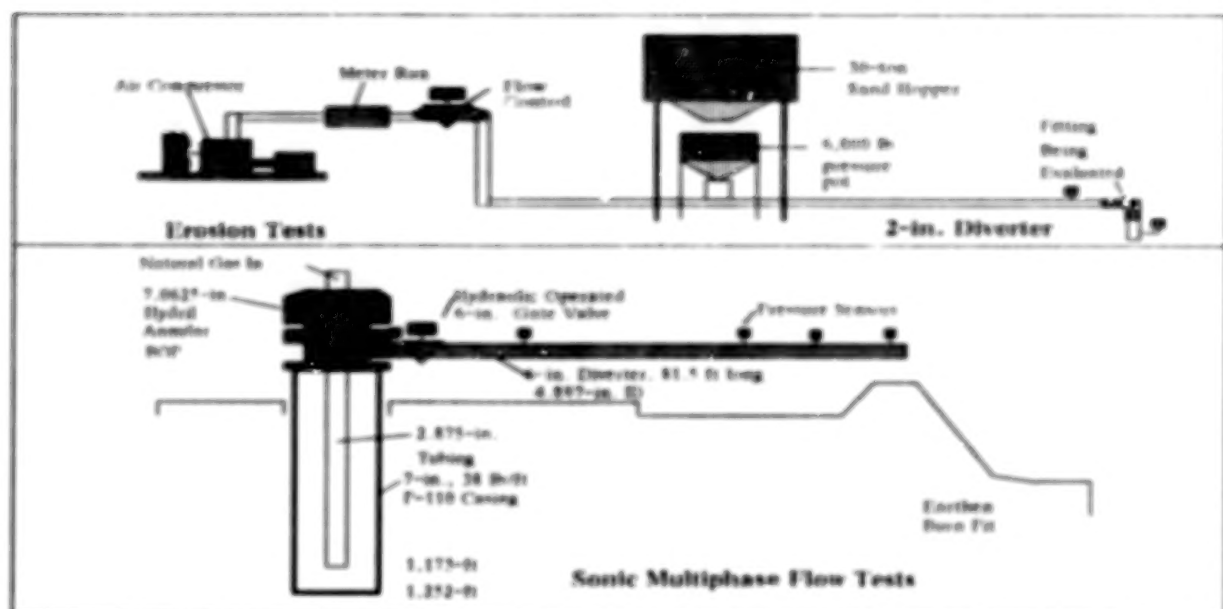


Figure 3 — Schematic of Model Diverter Systems.

3. Measurement of erosion rates and plugging characteristics in various types of diverter turns for steady state, multiphase flow of liquid/sand slurries and gas/liquid/sand mixtures.
- A number of model diverter systems were constructed at the LSU/MMS Research Well Facility in order to perform these experiments. A schematic of two models used is shown in Figure 3.

Summary

The experimental data obtained provided valuable insight into the controlling fluid dynamics mechanisms involved in the complex multiphase flow behavior of well/diverter systems at sonic and near sonic velocities. In the past, backpressure estimates were often made by assuming that the pressure in the diverter exit was atmospheric and the fluid acceleration term was negligible. The experimental data showed that these assumptions could result in large errors. Based on the data, improved methods for calculating the critical (sonic) flow rate and near sonic flowing pressure gradients were determined for two phase mixtures (Beck and others, 1986). Systems analysis procedures were then applied to develop a computer model of a gas-formation/well/diverter system (Beck and others, 1987). The computer program will model both surface and subsea diversions of shallow gas flows. Use of the program will permit the evaluation of the adequacy of a given conductor-casing/diverter design for handling a given gas reservoir without hydrofracture in the open borehole. The program will also calculate the maximum surface pressures and flow rates that would be experienced during the diverter operations.

The experimental data on erosion in bends due to produced sand showed that very rapid diverter wear can occur near sonic velocities (Johnson, 1987). This can be seen in Table 1, which gives representative results of some of the measured maximum rates of loss in wall thickness of various types of diverter bends. It was found that erosion rates are greatest for gas/sand mixtures. Introduction of formation water or drilling fluid to the mixture significantly reduced the erosion rates. For gas/sand mixtures, a plugged tee was found to be about an order of magnitude more erosion resistant than short radius ells for making a 90 degree turn. Long radius ells were significantly more erosion resistant than short radius ells, but did not perform as well as a plugged tee. For liquid/sand slurries, this order of performance was reversed but the observed erosion rates were about two orders of magnitude lower than for gas/sand mixtures. The measurements indicate that for currently used designs, a short diverter life should be

Fitting Type	Run No.	Superficial Gas Velocity (Ft/S)	Superficial Liquid Velocity (Ft/S)	No Slip Sand Concentration (Volume %)	Maximum Rate of Loss in Thickness (In./Hr)
Plugged Tee	j-26 r-2	365 0	0 84.1	0.069 8.0	0.7 0.0034
EB with r/d = 4.500	j-36	365	0	0.069	3.0
EB with r/d = 3.250	j-4	381	0	0.045	4.6
EB with r/d = 3.500	r-3	0	96.1	5.0	0.0038
EB with r/d = 2.875	j-13 r-1	350 0	0 75.5	0.072 6.0	7.0 0.00062
EB with r/d = 2.130	j-38	381	0	0.057	8.14
Vortice EB	r-4	0	92	11.0	0.0040

Table 1 — Representative Results of Erosion Tests.

expected if formation sand is produced in large quantities. Wells on diverters have been observed to produce large volumes of sand.

Conclusions

As a result of the work performed to date, the following conclusions can be drawn:

1. The effect of critical (sonic) flow at the diverter exit and the fluid acceleration term in the multi-phase flowing-pressure gradient calculation should not be neglected when calculating pressures in an operating diverter system.
2. A systems analysis procedure can be used for evaluating the adequacy of a conductor casing/diverter design for handling a given gas reservoir without hydrofracture in the open borehole. Use of this procedure indicates that the minimum possible diverter diameter decreases as the depth of the conductor casing increases.
3. Very rapid diverter wear can occur in bends of a diverter line when formation sand is being produced with formation gas. The rate of erosion was found to be about two orders of magnitude higher for gas/sand mixtures than for liquid/sand slurries.
4. Erosion in a diverter bend due to produced sand is greatly affected by the type of fitting used. About a tenfold increase in diverter life can be achieved through use of a plugged tee when making a 90 degree bend.
5. Because of the possibility of rapid failure due to erosion, rig evacuation is recommended whenever a conventional diverter system is used to handle flow from a shallow gas formation.
6. The erosion rates in a diverter system are approximately proportional to the gas velocity raised to the 2.5 power. This indicates that the use of a large diameter diverter with a partially restricted exit will greatly improve diverter performance. A systems analysis procedure can be used to select the size of the restriction used for a given conductor casing design.
7. Subsea diverters offer several advantages over surface diverters and should be further studied.

The work completed to-date has led to an improved understanding of the loads placed on a diverter system when handling a shallow gas kick. The computer program is being extended to include modelling

of unsteady state flow of gas-contaminated mud from marine risers. In addition, the computer program is being used to evaluate the feasibility of a novel subsea diverter design. Erosion tests are also being conducted for several other diverter components.

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Mukluk Ice Stress Measurement Program

Principal Investigator: Dr. G.F.N. Cox
U.S. Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03750

Objective: To investigate the magnitude and variation of ice stresses around an offshore gravel island.

Ice stress measurements around offshore arctic structures are needed for the development and verification of analytical ice force prediction models. A number of ice stress measurement programs have already been conducted (Croasdale and Frederking, 1986). In general, measured stress values have been lower than anticipated and the results from these studies have had a considerable impact on our understanding of ice-structure interaction and operating procedures in the arctic offshore.

In an effort to further our understanding of the magnitude and variation of ice stresses around fixed offshore structures, ice stress sensors were deployed around Mukluk, an artificial fill island situated in 15 m of water in Harrison Bay, Alaska as shown in Figure 1. Ice stress and temperature measurements were obtained from twenty-three sensors positioned at seven sites around the island (Figure 2). Data were collected from the beginning of March to the end of May, 1985. This paper summarizes the results of the Mukluk ice stress measurement program.



Figure 1 — Location of Mukluk Island in Harrison Bay, Alaska.

In early March, Mukluk was surrounded by grounded rubble resulting from the movement and pile-up of thinner ice earlier in the winter (Figure 2). The rubble was most extensive on the northwest side of the island, extending about 300 m from the structure. The larger pile-ups were about 15 m high. The first-year ice on the north, south, and west sides of the island was about 1.6 m thick. On the east side of the island the ice was thinner, 1.1 m, as a result of the southeast movement of the ice earlier in the winter. The ice had a characteristic C-shaped salinity profile with an average salinity of about 4 parts per thousand.

Ice stress measurements were obtained using the cylindrical biaxial stress sensor developed by Johnson and Cox (1980). A detailed discussion of the sensor design and performance can be found in Cox and Johnson (1983) and Cox (1984a). The sensor has been successfully used to measure thermal ice pressures in New Hampshire lakes (Cox, 1984b), and ice forces in Esso's caisson-retained-island (CRI)

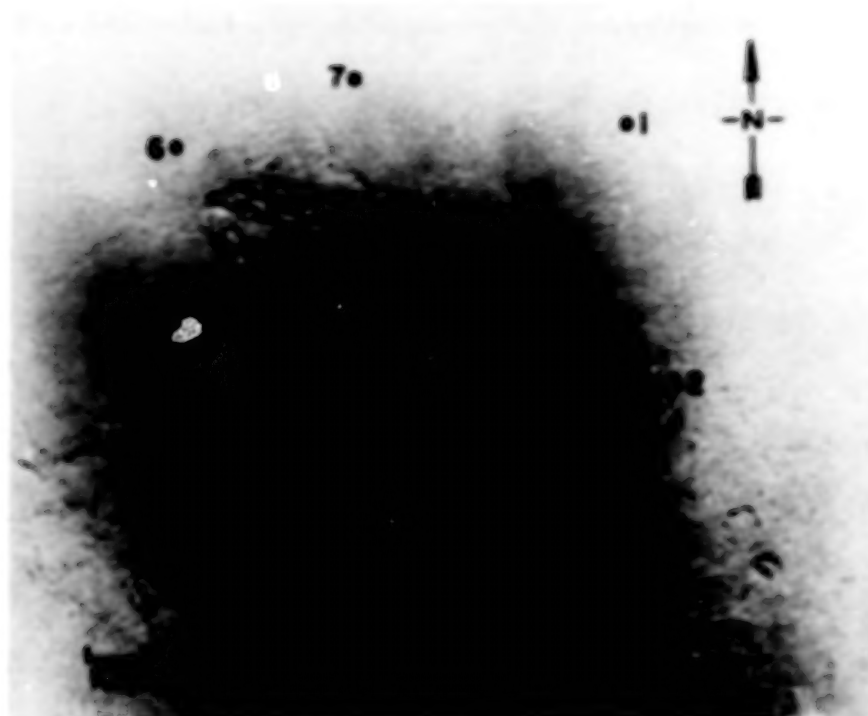


Figure 2 — Aerial Photograph of Mukluk Island Showing the Ice Conditions in the Area and the Location of the Ice Stress Measurement Sites.

in Mackenzie Bay (Johnson et al., 1985) and Adams Island in the Canadian Arctic (Frederking et al., 1984 and 1986).

Unlike the stress measurement program conducted by CRREL at Esso's CRI Kadluk location, where the data loggers operated in a heated building on AC power and were continuously monitored, the Mukluk program was an unattended, battery powered operation. Data loggers were placed on the ice and serviced at two week intervals. Unfortunately, some problems were experienced with the internal batteries in the data loggers which resulted in a number of gaps in the data record.

Two to four sensors were deployed at each of seven sites around the island. The number and depth of the sensors at each site are given in Table 1. Only two sensors were deployed at Site 2 as the ice in that area was only 1.1 m thick. Four sensors were placed at Sites 5, 6, and 7. Earlier in the winter, and in the previous year, major ice motions in this area were towards the southeast, so sensors were concentrated on the northwest side of the island-rubble complex.

Maximum and minimum stress readings for each of the stress sensors during the entire stress measurement program are presented in Table 1. Compressive stresses are taken as positive. An example stress-temperature record, Site 6, is shown in Figure 3. Here, for convenience, the stresses are resolved into north and east normal components and shear. Net ice motion data for each of the sites are given in Figure 4. The movements were determined from surveys of the ice stress sites at the beginning and end of the program.

The maximum measured compressive stress during the measurement program was 240 kPa and the maximum tensile stress was 340 kPa. In general, compressive and tensile stresses were usually less than 100 kPa and seldom exceeded 200 kPa. This is not too surprising as the meteorological data collected by Sohio on the island indicated that there were no major storms during the study. While the temperature data given in Figure 6 does show that there was a significant warming of the ice sheet after 25 April, thermal ice pressures were small. In contrast, maximum thermal ice pressures at Kadluk were about 500 kPa (Johnson et al., 1985). At the Kadluk location in Mackenzie Bay, the ice sheet was relatively fresh. In Harrison Bay, the sheet ice had a salinity of about 4 parts per thousand. As the ice in Harrison Bay was considerably more saline, it had a lower modulus and yield strength than the ice in Mackenzie Bay and was unable to sustain any significant thermal stress during warming.

Table 1 — Maximum (Compression) and Minimum (Tension) Stress Readings for Each of the Sensors.

Site	Depth (cm)	Sensor	Minimum (kPa)	Maximum (kPa)
1	38	608	-	-
1	107	708	-80	180
1	135	703	-310	200
2	38	609	-230	200
2	76	706	-140	220
3	76	704	-300	220
3	107	712	-160	10
3	135	711	-300	150
4	38	613	-	-
4	76	617	-260	200
4	122	714	-210	100
5	38	620	-260	190
5	76	621	-320	70
5	107	715	-200	240
5	135	719	-300	220
6	38	632	-90	120
6	76	720	-100	120
6	107	725	-60	80
6	135	726	-	-
7	38	636	-340	60
7	76	727	-110	160
7	107	728	-80	80
7	130	729	-110	120

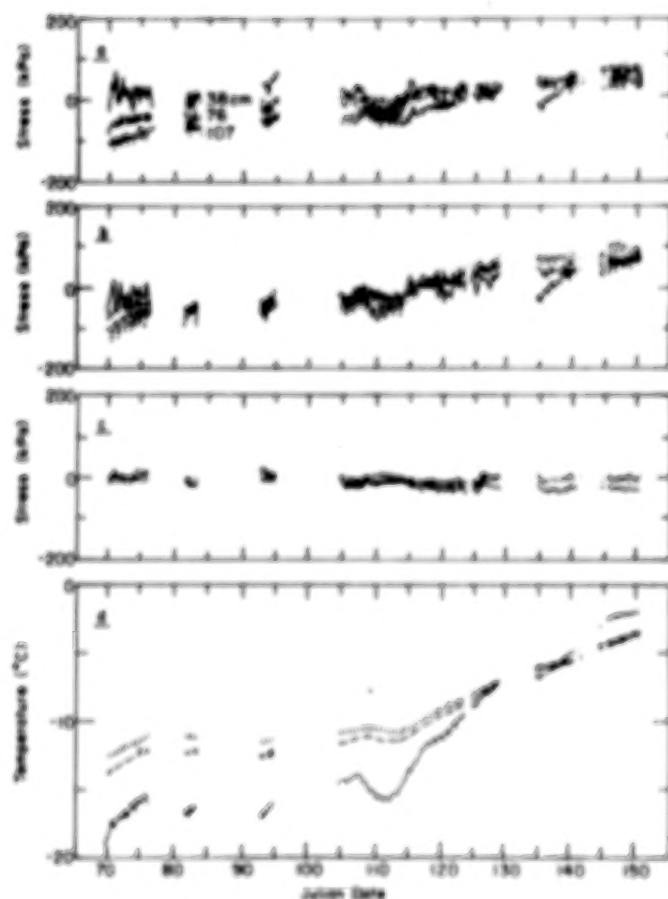


Figure 3 — Ice Stress and Temperature Data for Site 6; a) North Normal Stress Component; b) East Normal Stress Component; c) Shear Stress Component; d) Sensor Temperature.



Figure 4 — Net Ice Movement at Each of the Ice Stress Measurement Sites.

During the Kadluk ice stress measurement program, the direction of the principal stresses in the top, middle, and bottom of the ice sheet tended to be aligned when the stresses at all three levels exceeded 100 kPa. As stresses were generally lower than 100 kPa at Mukluk, there were only a few instances when the stresses were aligned through the full thickness of the ice sheet.

Analysis of the ice stress data did not reveal any systematic lateral variations in the ice stress during the first part of the program. For example, the daily mean magnitude and direction of the principal stresses on April 4 at each of the sites are plotted in Figure 5. Data at 76 cm were chosen as the sensors at this level provided the cleanest record and were close to the neutral axis of the ice sheet. In addition to the stresses being low, the ice stress measurement sites were probably too far apart to observe any continuum behavior in the ridged ice cover.

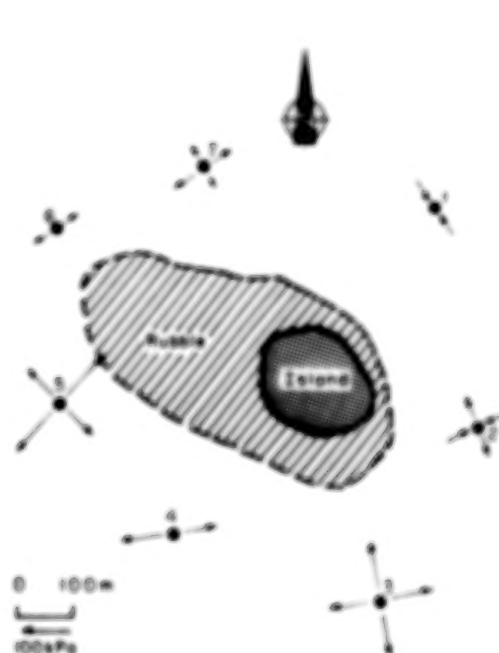


Figure 5 — Mean Daily Magnitude and Direction of Principal Stresses at 76 cm on April 4 (Julian Date 94). Converging Arrows Indicate Tension and Diverging Arrows Indicate Compression.

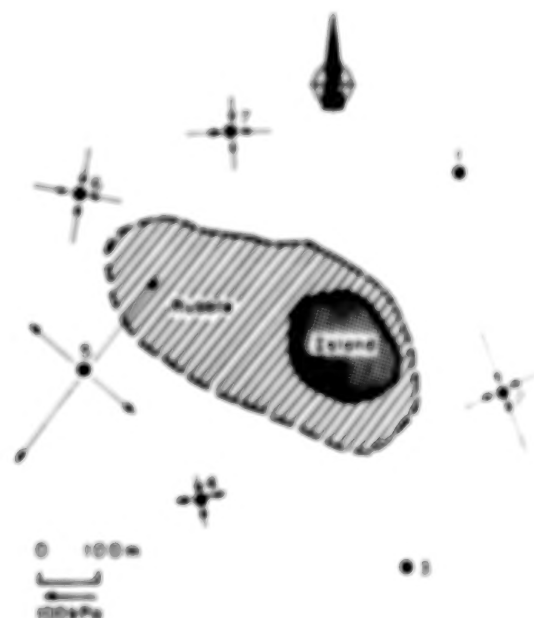


Figure 6 — Mean Daily Magnitude and Direction of Principal Stresses at 76 cm on May 29 (Julian Date 149).

Warming in late April and May induced thermal stresses in the ice cover resulting in an overall increase in stress in the ice sheet from a low tensile state to a compressive state. The mean daily magnitude and direction of the principal stresses at 76 cm on May 29 are illustrated in Figure 6. The stress at Site 5 at 76 cm is anomalous as nearly all of the sensors, regardless of depth and location, indicated compressive stress in both principal directions. In general, compressive stresses were higher on the north side of the island. This is in agreement with the southerly net ice movement shown in Figure 4.

It is interesting to note that variations in the air temperature each day resulted in diurnal oscillations in the stress record, not only in the upper portion of the sheet experiencing the greatest temperature change, but also at depth. Frequently when the ice sheet was in a state of bending, the change in stress at the top and bottom of the ice sheet were of opposite sign, that is, increased compression in the top fibers caused increased tension in the bottom fibers.

Conclusions

The Mukluk ice stress measurement program is yet another example of low ice stresses around an offshore arctic structure. While from a research and analysis perspective we are disappointed that no significant stress events were recorded, the results of this and recent studies should delight petroleum operators as they suggest that we have been overly conservative in estimating ice forces on offshore structures, particularly in areas of limited ice movement. During the course of the Mukluk program the ice sheet moved about 6 m towards the island; yet, maximum compressive stresses were only 240 kPa and usually less than 100 kPa. It is conceivable that Mukluk experienced its largest ice loads earlier in the winter during the formation of the rubble pile on the northeast side of the island. For this reason an effort needs to be made to measure stresses in the ice early in the winter prior to the formation of a rubble pile around the structure. Unfortunately, all ice stress measurement programs have usually been initiated in March when there is ample daylight for logistic support and ambient temperatures are not too cold to hamper personnel and equipment.

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Experimental Research for Pile Groups in Sand

Principal Investigators: Dan A. Brown
Department of Civil Engineering
Auburn University
Auburn, AL

Lymon C. Reese
Department of Civil Engineering
University of Texas at Austin
Austin, TX 78712

Objective: To conduct cyclic lateral loading tests on a full-scale pile group in order to evaluate group effects and compare with current design procedures.

The design of piles in sand for lateral loading is a common problem in foundation engineering. Most research has been directed toward the response of individual piles to lateral loads. However, piles are most frequently used in groups and little information is available on the effect of pile-soil-pile interaction on the performance of groups of piles subjected to lateral loading. Cyclic lateral loading is an aspect of the problem which introduces additional complexity and is encountered in offshore foundations as well as other applications.

A study was conducted at The University of Texas concerning the behavior of a closely spaced group of piles in sand when subjected to cyclic lateral loading. Full details of the research program are presented by Morrison and Reese (1986). The research included a large-scale load test of a group of nine steel pipe piles which were instrumented to measure the distribution of load to the top of each pile and bending stresses along the length of each pile. A similar load test was also performed on an isolated single pile for comparison. Several important aspects of the behavior of pile groups in sand are identified by these measurements.

The load test was performed in conjunction with other studies of pile behavior at the Foundation Test Facility on the campus of the University of Houston. As shown on Figure 1, soil conditions consist of 9.5 ft of medium dense sand underlain by very stiff clay. The piles were driven and load tested in the natural clay soil prior to excavating and backfilling to place the sand. Because the piles were not structurally damaged in the earlier experiment, the group was used for this research to obtain substantial additional experimental data at a relatively modest cost. The properties of the natural clay soil at this site were described in the report of the group test in clay (Brown et al., 1987) and in detail by Mahar and O'Neill (1983). Because the sand extends to a depth of slightly more than 10 pile diameters, the response of the piles to lateral loading is dominated by the response of the sand.

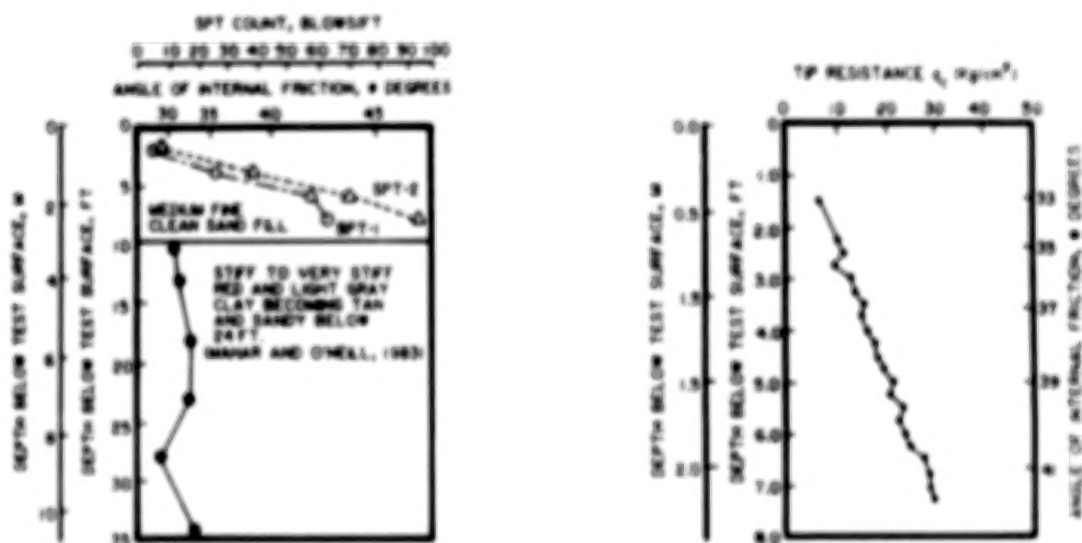


Figure 1 — Site Conditions and Results from Penetration Tests (after Ochoa and O'Neill, (1986)).

The sand was placed in a relatively dry state and compacted in 6-inch lifts to a relative density of about 50 percent using a Dyna-pac EY15 vibrating-plate compactor. The sand has a uniform gradation, is of medium density, and is classified SP by the Unified Soil Classification System. Results of direct shear tests indicate the compacted sand to have an angle of internal friction, ϕ of 38.5° for a dry density of 98.5 lbs/ft^3 . Results from cone penetration and standard penetration tests are shown on Figure 1, along with a correlation with the angle of internal friction. Pressuremeter tests were also performed in the sand and were reported separately (Little and Briaud, 1987). After each lift of fill was placed, the sand was slowly saturated from below using perforated PVC pipes which had been placed at the surface of the clay. The site was kept flooded until completion of the testing program.

The pile group consisted of nine steel pipes, 10.75 in. in outside diameter, with wall thicknesses of 0.365 in. The piles were arranged in a 3 by 3 group with a spacing of approximately 3 diameters on center. The layout of the test site and sand fill is illustrated on Figures 2 and 3.

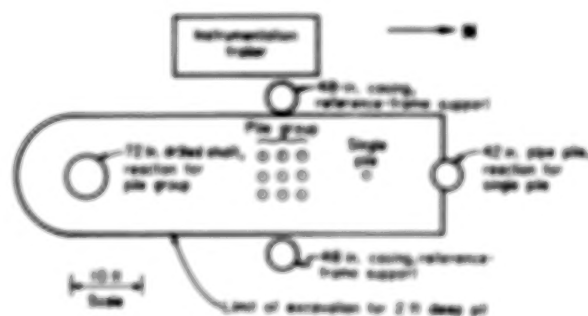


Figure 2 — Site Layout (1 ft = 0.305 m; 1 in. = 25.4 mm).

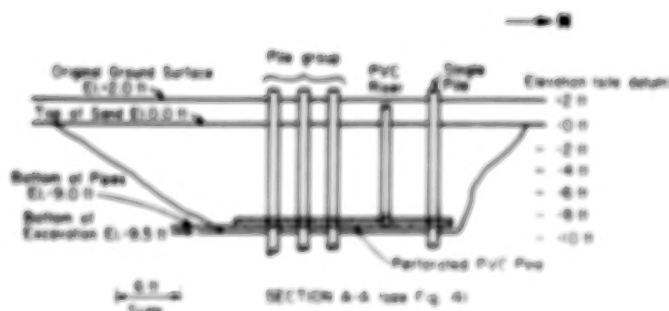
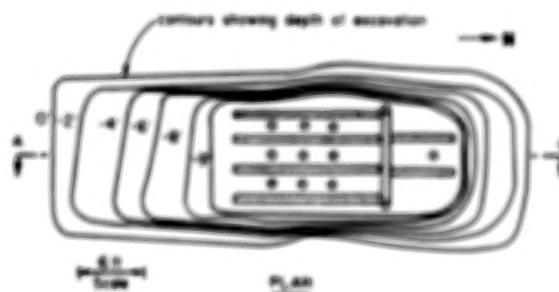


Figure 3 — Excavation and Pipe System for Saturating Sand (1 ft = 0.305 m).

In order to provide information on the response of the individual piles and surrounding soil during loading, a thorough program of instrumentation was performed. The instrumentation used for this experiment is essentially identical to that described by Brown et al. (1987). The testing arrangement was designed to load the piles through a rigid frame with pinned connections to the top of each pile. Instrumentation was directed at measuring the distribution of bending moments along each pile, the distribution of load to each of the piles, and the slope at the top of each pile. With these measurements, the soil resistance as a function of depth for each pile could be determined.

To measure bending moments, a pipe with a diameter of 6.625 in. was grouted into each pile. These pipes were instrumented with electrical-resistance strain gauges, as shown on Figure 4, to provide measurement of bending moment at various depths along each pile. The single pile was instrumented with gages on the exterior of the pile surface (Brown et al., 1987).

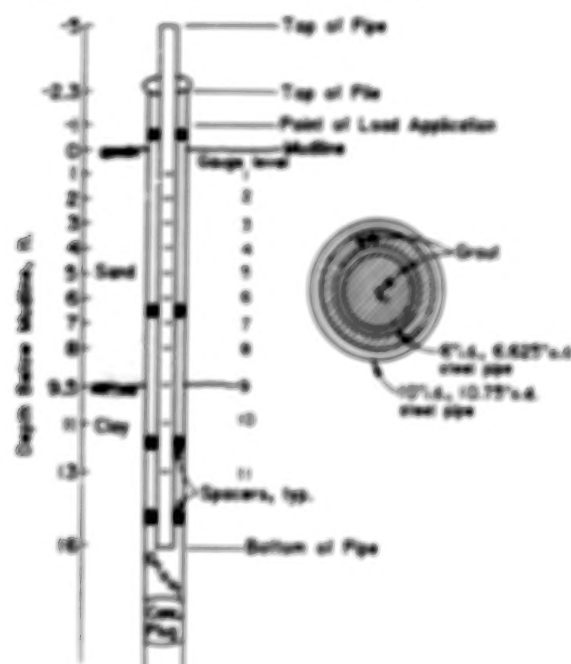


Figure 4 — Elevation View of a Pile from the Group Showing Location of Strain Gauges (1 ft = 0.305 m; 1 in. = 25.4 mm).

The piles were connected to the loading frame through a moment-free joint. A load cell at each connection provided a measurement of load to each pile. Load on the group was measured with a single load cell, which provided a check on the total of the loads from the individual pile load cells. Measurements of deflection and slope at the top of each pile were made using two linear potentiometers that were mounted to an independent frame at different heights above the point of load application.

Load was applied as a push or a pull using a double acting hydraulic cylinder. At each preselected load, the load was applied in either the "compression" or "tension" direction and the group deflection was measured. Cyclic loading was then applied using a computer-driven servo-controller to produce a sinusoidal curve of pilehead deflection vs time. The deflection found for the first cycle was maintained constant in both the compression and tension directions, thus allowing the load to vary for the 100 to 200 cycles of load at each load level. The frequency of loading was 0.067 Hz. Measurements of all of the instruments were recorded at selected intervals using a computer-controlled data-acquisition system. The same procedure was used in loading the isolated single pile.

As expected, the group as a whole was observed to deflect significantly more than the isolated single pile when loaded to a similar average load per pile. An examination of the pattern of load distribution to the piles indicated that the pile response was closely related to row position within the group; the piles in the front row were significantly stiffer than the piles in trailing rows. No distinct pattern emerged regarding the effect of position within a given row.

The general load-deflection response of the group is illustrated in Figure 5. Detailed results were summarized (Brown, et al.) and presented in some detail in Morrison and Reese (1986). Analyses of the test results allowed the following conclusions to be developed:

1. The deflection of the piles in the experimental group was significantly greater than that of a single pile under a load equal to the average load per pile.
2. The reduced efficiency of the group under lateral load was due principally to the effect of "shadowing". Piles in the trailing rows had a greatly reduced soil resistance because of the influence of the piles in the leading row. The soil resistance of the piles in the leading row was only slightly reduced below that of the isolated single pile.

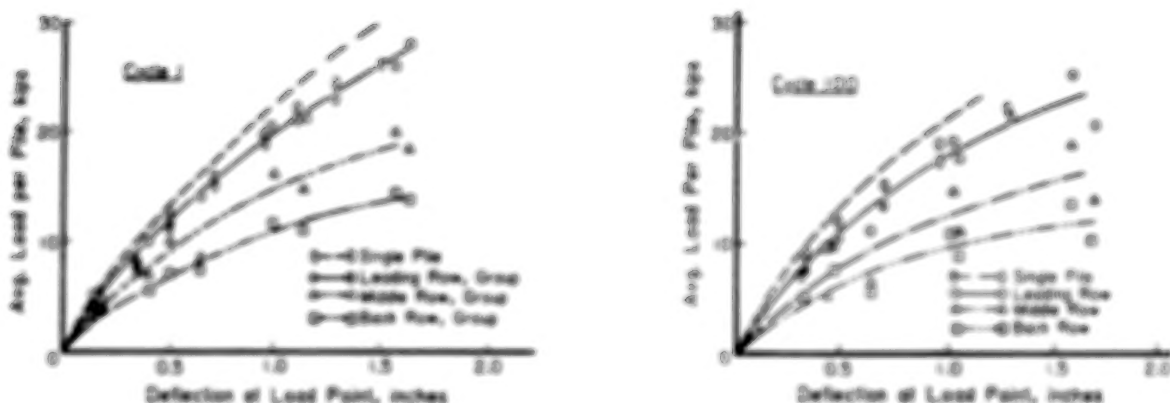


Figure 5 — Plots of Pilehead Load vs Deflection for the Single Pile and for the Group by Row Position
(1 kip = 4.45 kN; 1 in. = 25.4 mm).

3. Bending moments of the piles in the leading row were very similar to those for the isolated single pile under the same load per pile. The maximum bending moments in the trailing-row piles occurred at a greater depth and were larger for a given lateral load on those piles; however, because the load on the group was distributed in greater proportion to the piles in the leading row, the maximum bending moments for a given load on the group occurred in the leading-row piles.
4. Cyclic loading in two directions had a relatively small effect on pile response relative to similar tests conducted in clays. Some softening of the response of the piles in the group was observed at large loads (approaching pile failure); almost no effect occurred at small loads.
5. Significant densification occurred in the sand due to two-way cyclic loading, and may explain the relatively small loss of soil resistance due to cyclic loading. It is probable that one-directional cyclic loading would have produced greater loss of soil resistance and less densification. These observations underscore the importance of load history on the behavior of laterally loaded piles in sand.
6. The key to design of pile groups for lateral loading appears to be the development of rational methods for predicting the loss of soil resistance in piles within trailing rows. The loss of soil resistance in the piles of the leading row is less significant. A convenient way of expressing the loss in soil resistance due to group effect is with the use of a "p-multiplier," a constant used to modify p-y curves for an isolated single pile. The results reported herein should be useful in developing methods for predicting p-multipliers and provide designers with data for developing judgment.

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Dynamics and Reliability of Compliant Drilling and Production Platforms

Principal Investigator: Dr. Emil Simiu
Structures Division
National Bureau of Standards
Gaithersburg, MD 20899

Objective: To estimate errors and uncertainties in the modeling of compliant structure behavior with a view to developing techniques for the assessment of their structural reliability.

The construction, operation, and maintenance of oil and gas production facilities in hostile environments require innovative and frequently untried engineering solutions. The assessment of uncertainties and risk is, therefore, a key element in the planning, design, and operation of these facilities.

From previous work on this project it was determined that a useful, comprehensive scheme for the practical reliability analysis of compliant offshore structures does not exist and is unlikely to be developed in the foreseeable future. On the other hand, platform reliability can be effectively enhanced through improved knowledge of various aspects of structural loading, response, and resistance, and of uncertainties associated therewith.

In the period 1986-1988 work was completed on the following topics: the effect of second-order nonlinear inertia terms on the estimation of hydrodynamic damping forces on vertical cylinders in wave flow (Cook, 1987; Cook and Simiu, 1988); the effect on offshore platform response of using various versions of the Morison equation currently employed in ocean engineering practice (Velezios and others, 1986); and the experimental identification of actual dynamic response characteristics of large structures (e.g., tension leg platforms) by pulse probing and deconvolution (Carasso and Simiu, 1988). In addition, research was initiated on the application of recent results of statistical theory to the estimation of extreme climatological events, and on the potentially important implications of these results for the estimation of platform reliability. Research was also initiated on nonlinear platform dynamics problems involving complex and potentially dangerous behavior, including subharmonic resonances and chaotic motions.

In the keynote address to the 1979 BOSS Conference, Sir James Lighthill pointed out the absence of a second-order term of potential origin from the Morison description of the hydrodynamic force on a vertical cylinder. This term is due to the nonlinear interaction between the flow velocity and its horizontal gradient. Lighthill suggested that failure to include that term in the Morison equation could result in incorrect estimates of the hydrodynamic damping force, particularly for low values of the Keulegan-Carpenter number.

In view of the essential role played by hydrodynamic damping in controlling dynamic amplifications of tension leg platform motions due to wind loads, it was of interest to examine the effect of the Lighthill term quantitatively. This was done by deriving the expression for this term in the case of finite water depths, and by analyzing measurements obtained in periodic wave flow at the Naval Civil Engineering Laboratory and in random wave flow at the Delft Hydraulics Laboratory (Cook, 1987; Cook and Simiu, 1988). The results of the analysis showed conclusively that for both the periodic and random wave conditions the addition of the Lighthill term did not improve the Morison equation significantly and had no significant effect on the estimation of the drag force including the drag force corresponding to very low Keulegan-Carpenter numbers.

As an example, the solid lines in Figures 1 and 2 represent the measured hydrodynamic forces due to periodic waves with Keulegan-Carpenter number $KC=4.41$. The calculated forces based on the Morison equation and on the Morison equation with the addition of the Lighthill term as shown by the interrupted lines, and the differences between measured and calculated forces is shown by dash-dot lines. It is seen that these differences do not change perceptibly as a result of the inclusion of the Lighthill term.

Velezios and others (1986) presented a comparison of, and an improvement over, current techniques for taking the relative fluid-structure motion into account when estimating hydrodynamic forces on cylinders. Their study included comprehensive parametric studies of the maximum platform response

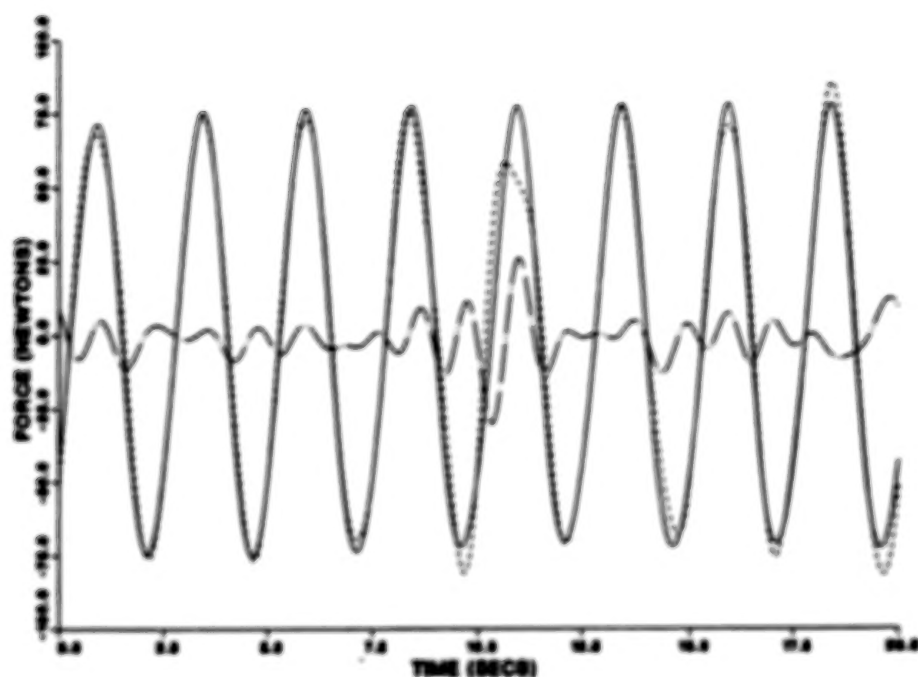


Figure 1 — Force Time Histories as Measured and as Modeled by Morison Equation, Keulegan-Carpenter Number $KC=4.41$.

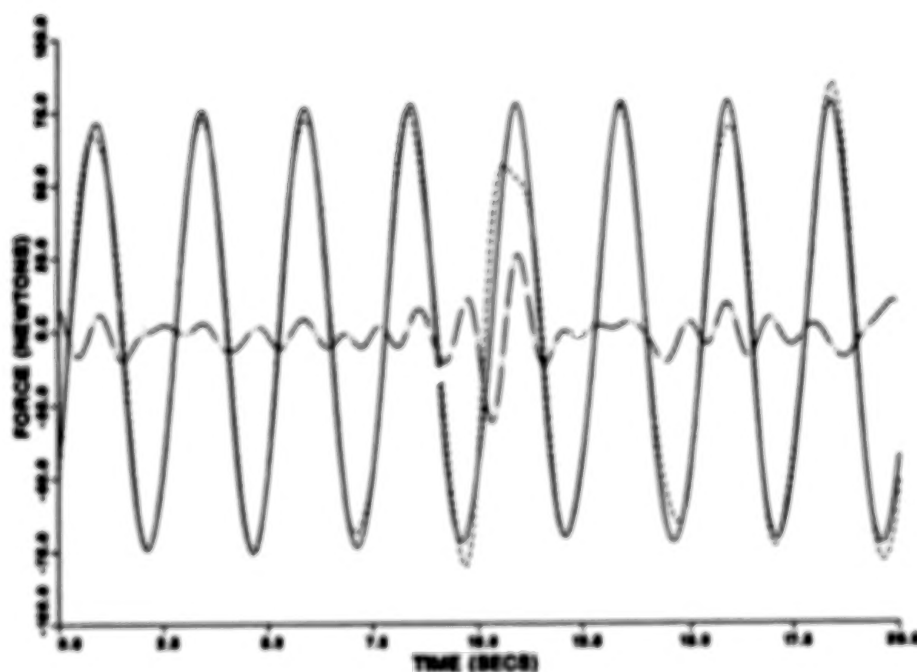


Figure 2 — Force Time Histories as Measured and as Modeled by Morison Equation with Lighthill Correction, Keulegan-Carpenter Number $KC=4.41$.

induced by several combinations of a simulated wave train and a constant-velocity current. It was shown that the accuracy of the approximate techniques being investigated depends significantly upon the relative magnitudes of the drag and inertia components of the wave loading.

These procedures may lead to substantial errors for structures for which the drag component of the exciting force is dominant and for which the fundamental natural frequency of vibration is substantially higher than the dominant frequency of the wave loading. An approximation was proposed for the

hydrodynamic modal damping factors of multi-degree-of-freedom systems, which can be useful for preliminary design decisions. Typical comparisons between "exact" solutions and solutions based on equivalent linearization techniques are shown in Figure 3.

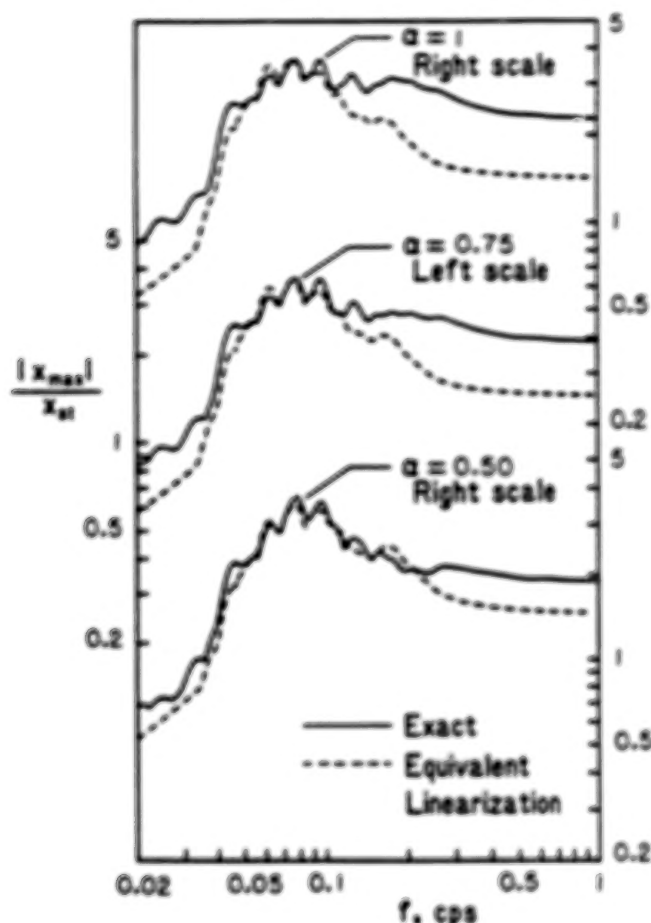


Figure 3 — Response Spectra for Systems Subjected to Wave Loading.

For innovative structures such as compliant platforms, analytical tools may not be sufficient for obtaining dependable information on actual dynamic behavior, and experimental information obtained under service conditions may have to be obtained. Such information may be used for validating results of analytical modeling; as input data in active control systems; and to monitor the integrity of the structure and the evolution of its dynamic properties in time. In principle the identification of the dynamic properties of the structure can be achieved by exciting the structure with a pulse, measuring the response, and obtaining the dynamic Green's function of interest from the measured response and the known pulse shape.

Once the Green's function, which can be regarded as the dynamic signature of the structure, is known, the corresponding dynamic behavior is fully defined. While this procedure is simple in principle, in practice considerable difficulties may arise owing to the unavoidable presence of measurement noise in the response data. The inverse problem of obtaining the dynamic Green's function from the response is mathematically ill-posed, that is, even minute noise levels in the response can result in enormous errors in the Green's function being sought. An example of such errors is shown in Figure 4, which represents the direct reconstruction, from response data contaminated by 0.5% noise, of the Green's function for a simply supported beam. The corresponding exact Green's function is shown in Figure 5. The errors inherent in the direct reconstruction are seen to be unacceptably large. To obtain useful estimates of dynamic Green's functions from noisy response measurements it is necessary to regularize the calculation procedure by filtering out high frequencies in a mathematically appropriate manner. A regularized, as opposed to direct, reconstruction of the dynamic Green's function from the noisy re-

sponse data that yielded Figure 4 is shown in Figure 6. It is seen that the regularized reconstruction is an excellent approximation to the exact Green's function of Figure 5. The mathematical and computational work that forms the basis of the procedure applied to obtain regularized reconstructions is summarized in (Carasso and Simiu, 1988), which also contains a number of illustrative applications.

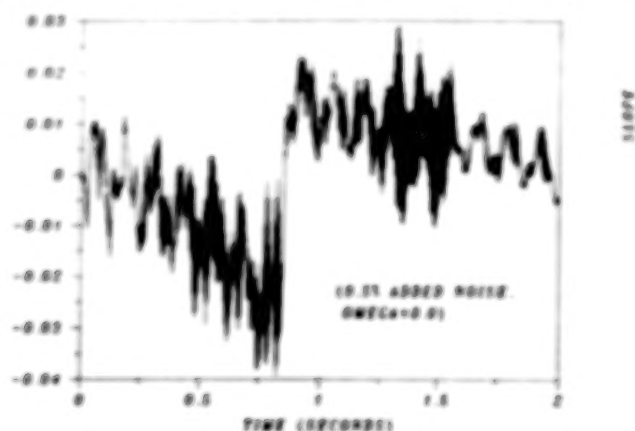


Figure 4 — Direct Reconstruction of Dynamic Green's Function.

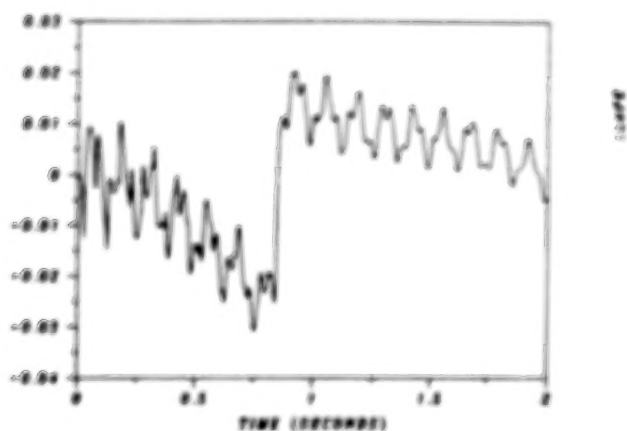


Figure 5 — Exact Dynamic Green's Function.

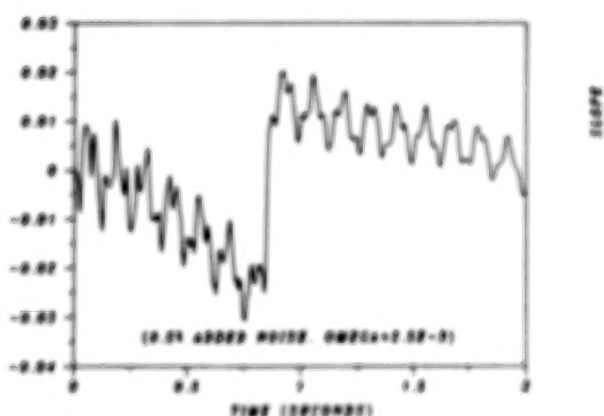


Figure 6 — Regularization Reconstruction of Dynamic Green's Function.

There are indications that current probabilistic models for describing extreme climatological events (e.g., extreme winds or extreme waves) may be unrealistic, and that reliability calculations based on such models might yield utterly misleading results. This statement is based on recent work which lends support to the hypothesis that, for various extreme climatological events, the probability of exceedance of certain thresholds is nil. Rather than being finite, as is implicit in the current assumption that the

probability distributions of interest have infinite upper tails. The project is currently engaged in an exploratory effort aimed at testing this hypothesis. The approach is methodologically similar to that described in (Simiu and Scanlan, 1986), and is based on recent developments in extreme value theory (Smith, 1985). The approach is based on comparisons between the analysis of extreme data measured at a large number of locations, on one hand, and of synthetic extreme data obtained by Monte Carlo simulation from the distributions being tested. The results of this investigation could strongly influence the evolution of structural reliability theory as applied to offshore structures and other structures designed for extreme climatological events.

It has recently been shown that compliant structures can exhibit complex and potentially dangerous dynamics involving subharmonic resonance and chaotic behavior (Thompson and Stewart, 1987). These phenomena arise when the system is nonlinear, as is the case for compliant structures, particularly near their limit states. Nonlinear systems can have multiple steady states dependent on the initial conditions of the motion. Unless these multiple states and their respective sets of initial conditions are known to the analyst, computer calculations may miss precisely those solutions that would control the design. The analyst should also be aware of circumstances in which dynamic motions may exhibit sensitivity to initial conditions, leading to divergence of solutions with adjacent initial starts, and the consequent unpredictability of future behavior that characterizes chaotic behavior.

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Seafloor Seismic Data Study

Principal Investigator: Gerard E. Sleaf
Advanced Technology Division 6258
Sandia National Laboratories
Albuquerque, NM 87185

Objective: To design, develop, install, and monitor seafloor seismic stations and to analyze seafloor motion records to provide a seismic characterization of offshore oil and gas leasing regions.

A significant consideration in the design of offshore structures is their response to environmental stimuli. Information regarding climatic and oceanographic environmental stimuli for most offshore areas is extensive. These have yielded a solid foundation on which to base structural design to meet the threats of storm winds, waves, and ice flows. In regions such as offshore southern California and offshore Alaska, an equally important environmental stimulus is the seismic vibrations induced by local earthquakes. Data on the response of seafloor sediments to earthquake-induced seismicity has been scarce, thereby introducing significant uncertainty into the seismic-hazards aspect of offshore structural design. To reduce this uncertainty a program was undertaken to develop and implement instrumentation to measure seafloor seismic motions. The result of this program has been the offshore recording of several significant earthquakes. Two of the earthquakes recorded by the subsea's instrument were simultaneously recorded by on-shore instruments, and by instruments located on a nearby offshore oil platform. Thus, some of the problems associated with the design of offshore earthquake-resistant structures can now be addressed with supporting data.

The Seafloor Earthquake Measurement System (SEMS) consists of two subsystems; a seafloor package and a shipboard unit as illustrated in Figure 1. The seafloor package captures and records seismic activity, and transfers the data on-command to the shipboard subsystem via an underwater telemetry system. The shipboard unit records the telemetered digital data on magnetic media.

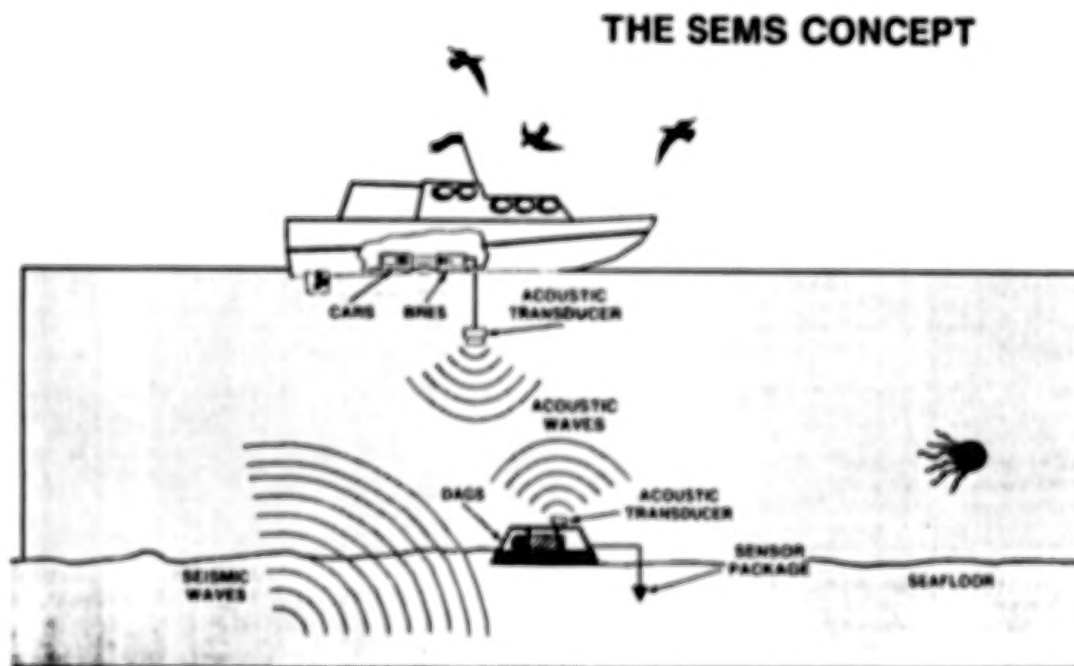


Figure 1 — Illustration of Seafloor Earthquake Measurement System (SEMS) Concept. SEMS Incorporates Both Long-Term Data Recording and Data Telemetry.

Situated on the seafloor is the seismic instrumentation package. The seafloor electronics package, referred to as the Data Gathering System (DAGS), is connected to a seismic probe which is embedded in the seafloor sediments. The probe consists of three accelerometers, configured tri-axially, to record the seismic motions, and a two axis magnetometer to determine the absolute orientation of the accelerometers. DAGS consists of a microcomputer controller, a data acquisition interface, volatile Random Access Memory (RAM), permanent non-volatile bubble memory, an acoustic telemetry system, and a battery power pack. The major attributes of the DAGS include a low power consumption for extended system life; a broad seismic dynamic range-sensing capability; an efficient use of limited digital data storage capacity; and a remote interrogation of the system from the surface. Low power consumption is achieved by use of CMOS technology and other low power components wherever possible. The non-volatile magnetic bubble memory is used for long-term data storage and is only activated when significant earthquake events are detected. This bubble memory device has the advantage that it can be de-energized for long periods of time without loss or degradation of stored data.

The SEMS uses low power accelerometers which are capable of measuring acceleration levels from 0.05 milli-G's to 10 G's over frequencies ranging from 0.2 Hz to 20 Hz. Each accelerometer signal is digitized at a 100 Hz rate by a high-precision data acquisition subsystem. The digital accelerometer data is placed into volatile RAM and analyzed by the microprocessor. The DAGS incorporates earthquake event detection through the use of pre-trigger RAM buffering. The RAM is used to hold data while a determination is made whether these data should be saved or discarded. Short-term and long-term running averages are calculated and used to define the strength of seismic activity. If the system declares that the current data correspond to an earthquake event, then the data are stored in the bubble memory. Allocation of the bubble memory is based on a hierarchical scheme which retains only the most significant seismic events.

Communication with the seafloor package is accomplished with the use of an acoustic telemetry data link. The DAGS can be controlled from a surface computer, thus allowing data retrieval, diagnostic analysis, and variability in operating parameters. The surface instrumentation consists of acoustic transmitting and receiving circuitry, referred to as Buoy Repeater System (Bres), and a controlling IBM PC compatible computer. The PC serves as a user-friendly interface and allows direct communication with the seafloor instrumentation package. Additionally, data retrieved from DAGS is stored on floppy disks, and the earthquake data can be analyzed and graphically viewed on-board the ship during the interrogation.

The SEMS project was established in 1977 upon which a two-year effort was begun to develop prototype hardware. During 1979 and 1980, four prototype units were placed in the Santa Barbara Channel, offshore California reported in Ryerson (1981). These prototypes were designed primarily to respond to the frequent small local earthquakes typical of the Channel and had a one year life. These prototype units recorded at least 8 local earthquake events. In addition, the Santa Barbara Island Earthquake of 4 September 1981, a magnitude 5.9 on the Richter scale earthquake, was simultaneously recorded by two SEMS units. One of the SEMS units was situated under 165 ft of water, 85 km from the earthquake epicenter. The second recording unit was situated on-shore, 98 km from the epicenter. The recording of the same event both on-shore and offshore represented a unique data set at that time.

Between 1982 and 1984, the SEMS system was upgraded to serve as a long-term seismic station for offshore Alaska. A second generation prototype system was developed, and was deployed as a demonstration system offshore Long Beach, California in 1985 detailed in Hickerson and Lopez (1987). This system was designed to respond primarily to strong motion earthquakes, and had a 2.5 year life. This system recorded two significant earthquakes during the month of July, 1986 [Sleece and Engi (1987)]. The earthquakes recorded were the 8 July North Palm Springs Earthquake and the 13 July Oceanside Earthquake. The earthquake epicenters and the SEMS location are illustrated in Figure 2. Located about 2 km south of the Long Beach SEMS site is the instrumented Shell Platform Eureka, Husid, et al. (1985), which also recorded the July 1986 earthquakes. Sandia has acquired the mudline-level platform acceleration records and compared these records with SEMS records and data obtained from on-shore seismographic networks, Huang (1986) and Porcella (1987).

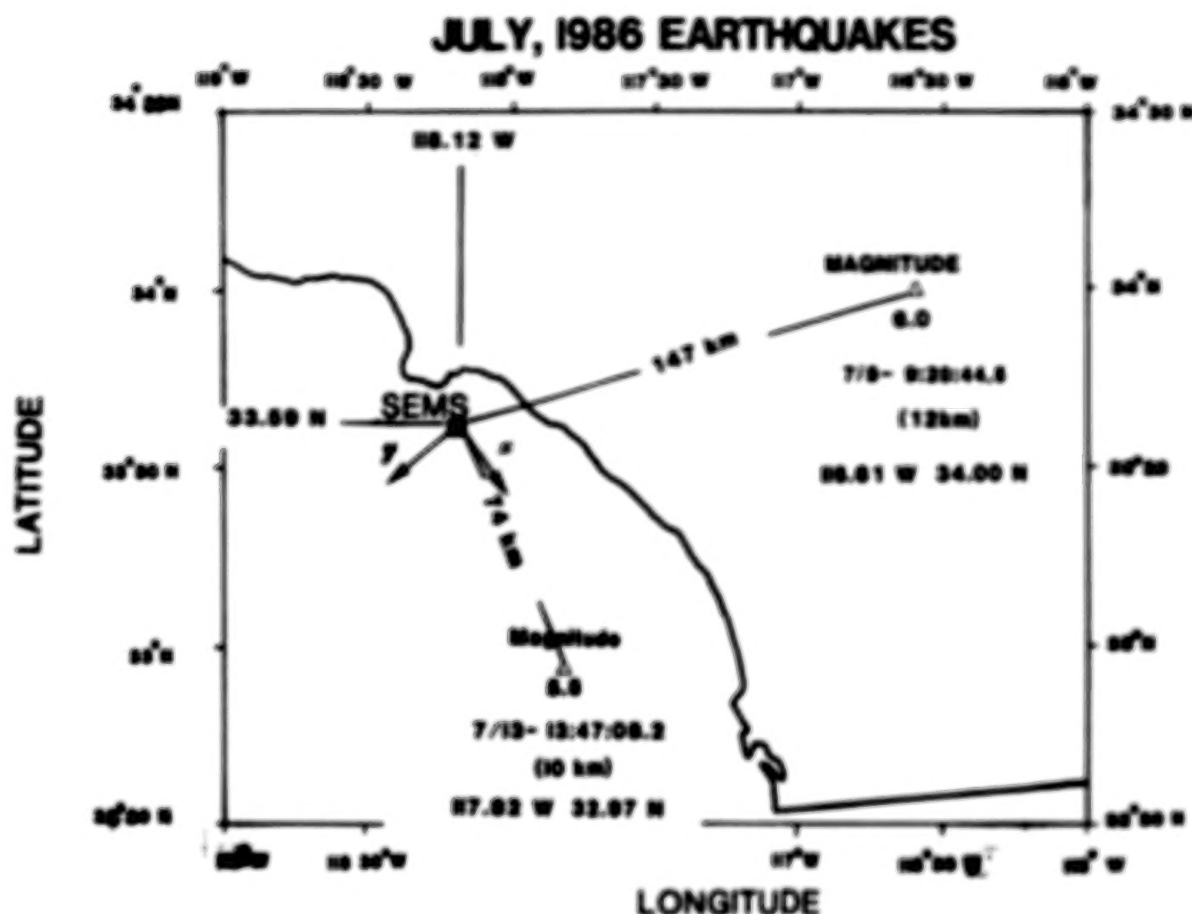


Figure 2 — Map of Southern California Showing Location of Two Earthquakes (Indicated by Triangles) Recorded by SEMS. The Magnitude, Time of Occurrence, Depth of Focus, and Coordinates Are Indicated for Each Earthquake Event. The Location of SEMS and the Orientation of Its x and y Accelerometers Are Also Indicated.

- The vertical component of acceleration observed at both the SEMS' site (i.e. free-field seafloor motion) and on the platform legs is significantly different than the corresponding vertical components of acceleration observed on-shore. A statistical analysis has shown that the offshore peak vertical accelerations are an order of magnitude weaker than the corresponding on-shore measurements.
- It appears that the peak horizontal components of acceleration observed at the SEMS site and by the platform legs are comparable to the corresponding on-shore measurements. Additional earthquake data obtained from future earthquakes will be required to either confirm this observation or point out the subtle differences between on-shore and offshore horizontal accelerations.
- While both SEMS and on-shore records have fairly broadband response spectra, the platform data indicates a fairly narrow-band response spectra. The narrow-band nature of the platform data is due to the excitation of the platform's resonant modes.

The above conclusions have important implications for the design of offshore structures. It is clear that the design process for offshore structures will greatly benefit from earthquake data obtained offshore.

The present goals of the SEMS program are (1) to verify, or if necessary, modify, existing models for predicting the response of saturated sediments to earthquake-induced seismicity; and (2) to deploy third generation offshore seismic stations. Sediment-response prediction modeling is generally based on one of three methods. 1. *Analytical Approach*. With this method, ground motions are computed by using analytical models. The models involved would generally include: source mechanism modeling, wave propa-

gation modeling, and soil response modeling. 2. *Empirical Approach*. With this method, seismic predictions are made based on previous observations of recorded ground motion. The empirical approach is usually based on a regression analysis which can include parameters for source mechanism and soil types, or 3. *Combined Analytical and Empirical Approach*. With this method, the best aspects of the analytical and empirical approaches are combined.

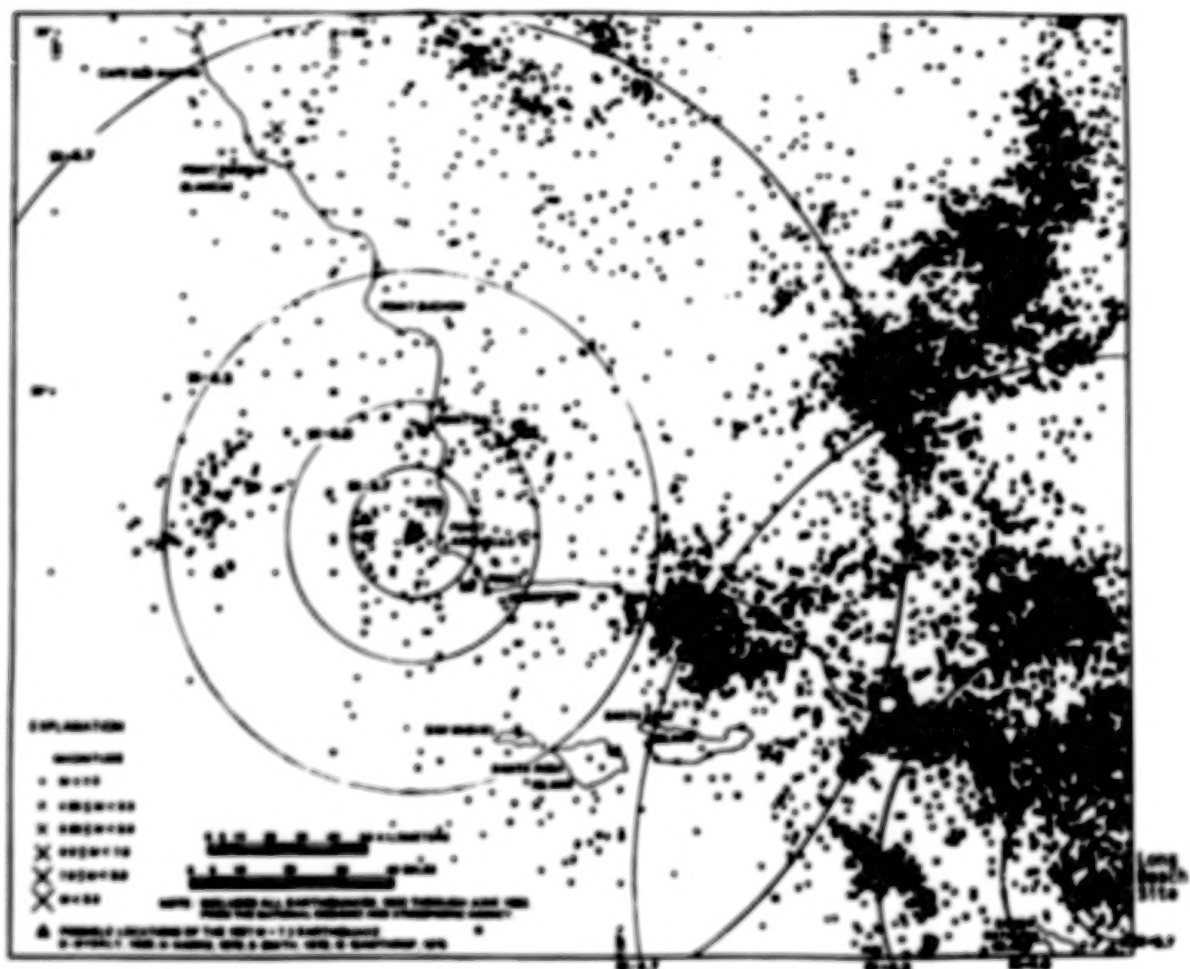
Sandia will investigate each of the above modeling methodologies. Work on the analytical approach is being performed in cooperation with research on-going at the Scripps Oceanographic Institute, Nogi (1988). Modeling approach 3 will be considered upon the completion of studies involving approaches 1 and 2.

Sandia is presently active in the design of a third generation offshore seismic station, referred to as SEMS III. SEMS III is an electronics upgrade of SEMS II. The SEMS III electronics are designed to serve as a general purpose seismic station for implementation offshore both California and Alaska. To be of practical use, it needs to be sensitive to both the relatively small earthquakes observed off the coast of California, and the strong motions typical of offshore Alaska. In order to sense small earthquakes, two features are necessary: low noise levels, and high gain. Low noise operation is obtained by both on-board hardware filtering and real-time software digital filtering. High gain operation is enhanced by triggering off of the horizontal accelerometers rather than the vertical accelerometers. The offshore horizontal motions are an order of magnitude stronger than the vertical motions. The difficulty with a horizontal component trigger is that vertical p-wave motions can occur many seconds before the horizontal motions begin. Extensive pre-trigger buffering is incorporated in the system so that the vertical p-wave arrival can be recorded if the system triggers on the horizontally-polarized shear wave. Additional features of SEMS III include a 6-7 year operational life and advanced diagnostics and calibrations during interrogations. An extensive research effort will be required to develop an unmanned deployment technique suitable for deep, rough waters. Deployment technologies being considered include probe emplacement by a vibrocoring drill and complete system emplacement by a boat-launched seabed penetrator.

The intended sites for SEMS III offshore California are indicated in Figure 3. The first deployment site is offshore Long Beach near Shell platforms, while the second deployment site is offshore Point Arguello near Union Oil of California platforms. Also indicated in Figure 3 is the location and magnitudes of detected earthquakes over a 50 year period. SEMS III calculated sensitivity to earthquakes is indicated by circles around the SEMS site. It is seen from Figure 3 that SEMS will be capable of accurately measuring all earthquakes of magnitude 4.0 or greater within a 40 km radius of a SEMS site. Based on the seismic history near the SEMS sites, there is a high probability that the deployed SEMS units will record several of these smaller earthquakes during their lifetime. An additional feature of the offshore California SEMS units is that they form a seismic array for moderate-to-large earthquakes. Specifically, the two units will be capable of simultaneously recording earthquakes of magnitude 4.7 or larger in the Santa Barbara Channel. Earthquakes of magnitude 5.0 or greater in the Los Angeles Basin and on portions of the San Andreas Fault will also be simultaneously recorded by the two SEMS units. The large amount of data collected by SEMS III will provide invaluable offshore seismic information.

Sandia National Laboratories is involved in the offshore measurement of earthquake-induced seismic motions. Several prototype units have been deployed off of California and have resulted in unique offshore seismic data. These data are invaluable to designers of offshore structures and to government agencies that regulate those structures.

It is estimated that between 10% and 20% of the U.S. arctic oil reserves are situated in the southern Bering Sea. In order to extract these reserves, offshore platforms must be designed which can withstand the frequent, large earthquakes that are characteristic of that area. Due to significant geologic differences, seismic data obtained offshore California may not be relevant to offshore Alaska. Hence, it is necessary to acquire offshore seismic data for Alaska in order to aid in the eventual development of offshore-Alaska energy resources. Sandia's long term goals are to deploy an array of seismic stations in the Southern Bering and Aleutian region, Hickerson (1984). Such an array will answer many of the uncertainties regarding the earthquake-resistant design of offshore structures.



SEMS III SENSITIVITY TO EARTHQUAKES

Figure 3 — Map of Southern California Showing Seismicity During 50 Year Period 1932-1982. Also Shown are Future Locations for Two SEMS Sites. The Circles Indicate the Distance From SEMS Site That an Earthquake of a Given Magnitude can be Detected by SEMS.

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Wind Induced Oscillation Damage

Principal Investigator: Dr. Owen M. Griffin
Center for Fluid/Structure Interactions
Naval Research Laboratory
Washington, D.C.

Objective: To assess wind induced oscillation damage to offshore platforms under tow.

Many structural and environmental factors complicate any analysis of a system such as an offshore platform. These factors include variable relative wind speed, direction and duration; member configuration, end conditions and mass properties; and variations in tow speed and conditions. Due to both time and economic constraints, some attempt at a first-order deterministic analysis is the only viable approach for a preliminary damage assessment. More complicated time and/or frequency domain analyses to account for the non-resonant or random nature of the vibrations and a finite element analysis of the structure's natural frequencies may be required to fully satisfy the project's long-term economic and operational objectives.

Even when the random, vortex-induced strumming vibrations of a long ocean cable are considered, as by Kim et al. (1984, 1985), for example, the knowledge gained from first-order deterministic analyses has provided indispensable guidance.

Vortex-induced vibrations significantly increase the steady drag force on a riser, tubular or other similar member. Increases in drag coefficient of up to 250 percent for a structure in water are common and well documented (Griffin, 1985), even for relatively long riser and cable segments which vibrate in a direction normal to a uniform current (Griffin and Vandiver, 1983). It is known, however, that the drag is dependent directly upon the local vibration amplitude along the structure, so that the increased drag is reduced somewhat when the flow is not spatially uniform and the vibrations are non-resonant or random (Kim, 1984).

Vortex-induced vibrations of a cylindrical member in air are reduced from the comparable levels reached in water by as much as a factor of ten (Griffin, 1984; Simiu and Scanlan, 1986). The reduced level of the vibrations is accomplished by a similar reduction in the drag due to vortex shedding. Typical measurements of the amplitude of displacement normal to an incident flow of air are shown in Figure 1. The predicted line shown in the figure was calculated using an equation developed in a previous MMS-sponsored report (Griffin, 1985).

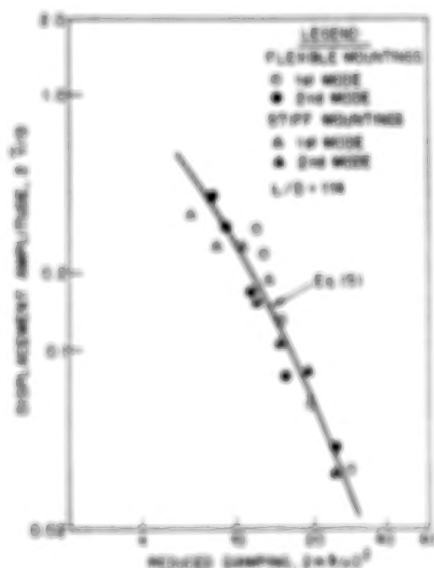


Figure 1 — The Wind-Induced Peak-to-Peak Displacement Amplitude Due to Vortex Shedding as a Function of the Reduced Damping; from Griffin (1984).

Fatigue is an important consideration in both air and water when the vortex-induced vibrations occur at the respective amplitudes of displacement in both media over a sustained time period. These unsteady fatigue stresses are superimposed directly on the increased mean stresses caused by the steady aerodynamic or hydrodynamic drag forces on the member. Thus the cumulative effects of the steady and unsteady stresses must be considered in any assessment of damage as in the present case where relative wind-induced vortex shedding is likely to be an important factor. A mitigating factor at the present time is that such an assessment is restricted to deterministic methods which tend to be somewhat conservative.

Various means for reducing and/or eliminating vortex-induced vibrations (VIV) have been developed in recent years. Extensive discussions of vibration suppression pertinent to marine engineering applications have been given by Hafen and Meggitt (1977), Every, King and Griffin (1982), and Gardner and Cole (1982). It generally has been found that mass and damping control is ineffective in water, so that some type of external device fitted about the member is required.

Control of the mass and damping of the structure is an effective measure for suppressing vortex-induced vibrations in air (Zdravkovich, 1984). However, external devices such as the helical strake winding often are used in air. Suppression of the vortex-induced vibrations was not feasible in the case of a recent platform because of the complexity of the jacket structure and, more importantly, because the problems encountered during the trans-Pacific tow and offshore demurrage periods apparently were not anticipated beforehand.

An assessment using the approach developed for this study can be made to determine the likelihood that relative wind-induced vortex shedding was the cause of vibrations which damaged the platform members. This analysis includes the effects of vortex lock-on and relative wind magnitude and direction, the expected amplitudes of displacement, the expected levels of the mean aerodynamic forces on the member, and, briefly, fatigue effects. Information pertaining to a particular platform configuration, and the dimensions and properties of the structural members under consideration is given in Table 1.

Table 1 — Offshore Jacket Platform Damage Assessment—Pertinent Structural Dimensions and Parameters.

Structural Member Properties/Parameters:

Length, $L = 90$ ft
Diameter, $D = 36$ in.
Wall thickness, $d = 0.875$ in.
Structural mass, $m = 300$ lb _m /ft
Structural damping (log decrement), $\delta = 0.01$

The assumptions which apply to an analysis of wind induced vibrations are that the platform legs and braces are modelled as long, slender cylindrical members dominated by stiffness (tension low, structural stiffness most important); structural mass properties are uniform lengthwise along the member and are well-defined; the relative wind magnitude and direction are slowly-varying; only the flow component normal to the member is important in exciting the vibrations; a subcritical Reynolds number ($Re < 10^5$) design data and methods can be employed with some confidence. The Reynolds number corresponding to the platform demurrage conditions was approximately $Re = 10^5$, but any applicable data are very scarce at such a high value of Re . These have proven to be reasonable assumptions under most circumstances for the analysis of problems similar to the present one.

The natural frequencies of the members can be estimated to a reasonable first approximation by considering them to be stiffness-dominated cylindrical beams. This neglects the interdependence of the

subelements of the overall structure, but has proven to be a reasonable first approximation. The frequencies of the first n natural modes are given by

$$f_n = \frac{\alpha_n^2}{2\pi l^2} \sqrt{\frac{EI g_n}{m_n}}, \quad \alpha_n = \alpha_1, \alpha_2, \dots \text{etc.}$$

where E = Young's Modulus, lb_f/ft^2 ;

I = moment of inertia, ft^4 ;

m_n = structural mass, lb_m/ft ;

g_n = proportionality constant, $32.2 \text{ lb}_m \text{ ft}/\text{lb}_f \text{ sec}^2$.

There are no added mass effects on the in-air natural frequencies. The natural frequencies can be calculated in a straightforward manner and are listed in Table 2.

Table 2 — Offshore Jacket Platform Damage Assessment

Mode Number, n	PREDICTED NATURAL FREQUENCIES AND RELATIVE WIND SPEEDS		Relative wind speed range, V_{1n}, V_{2n} (ft/sec, kt) ^a	
	Natural frequency, f_n (Hz)			
	pinned-pinned	clamped-clamped	pinned-pinned	clamped-clamped
1	1.10	2.10	14.8/24.7 (8.8/14.7)	14.1/14.8 (10.2/11.4)
2	4.42	6.97	18.1/28.4 (10.2/16.0)	14.0/14.8 (10.2/11.4)
3	8.94	13.7	174.1/225.1 (79.4/102.1)	184.8/208.1 (109.4/132.1)
4	17.7	22.6	-----	-----
5	27.6	33.7	-----	-----

^aRelative wind component normal to structural members.

This first-order approximation to estimating the natural frequencies has proven to be sufficiently accurate. The first mode natural frequencies of the members in question were found to be in the range $f_n = 1.5$ to 2 Hz .

Vortex lock-on and resonant, crossflow vortex-induced vibrations take place in air when the reduced velocity $V_r = V/f_n D$ is in the range $V_r = 4.5$ to 7.5 , for a member of circular cross-section. This is somewhat narrower than the comparable range in water, which is $V_r = 4$ to 11 . The relative wind speeds in the range of vortex resonance can be estimated from the relation

$$V_{1n}, V_{2n} = 4.5, 7.5 (f_n D) \text{ ft/sec.}$$

which represents the normal or exciting component of the relative flow. The total relative wind speed range is given by

$$V_1, V_2 = V_{1n}, V_{2n} (\cos q)^{-1},$$

where, in the present case, $q = 45^\circ$. The subscripts 1 and 2 respectively denote the lower and upper wind speed limits of the resonance.

The first five natural frequencies are listed in Table 2 for both pinned and clamped end conditions, together with the predicted range of relative wind speeds (normal component only) which correspond to vortex resonance. Only the wind speeds pertinent to the first three modes are given, since higher speeds

are probably of no practical consequence. The very highest relative speeds would be attained only when the platform was under tow into a strong, steady wind for an extended time period. (It is assumed here that the tow speed might be 5 to 10 kt.) The total relative wind speeds for the first three modes are plotted in Figure 2. Assuming that the true natural frequencies of the cylindrical members lie in the range between those approximated by pinned and clamped end conditions, one may expect that vortex-induced vibrations in the first mode are most likely to be encountered in the noted range of relative wind speeds.

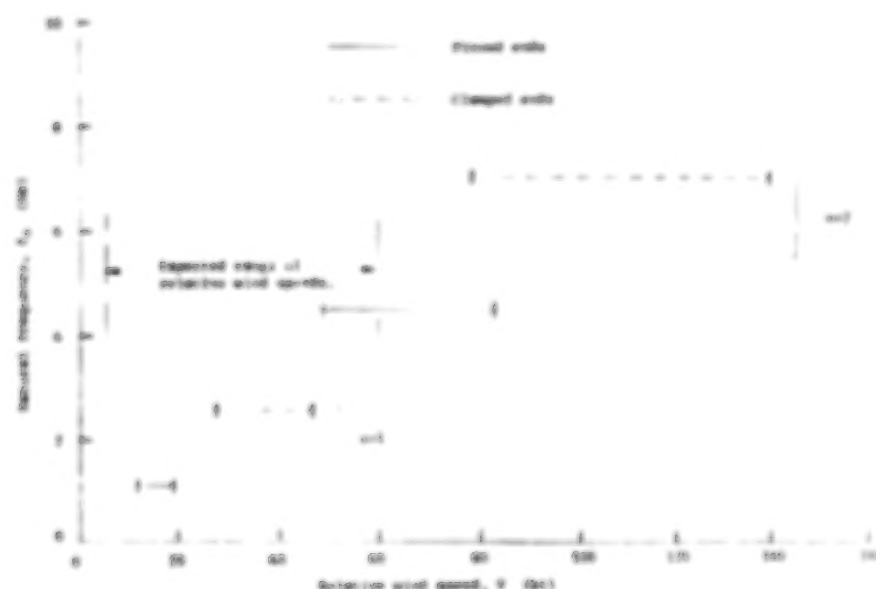


Figure 2 — Predicted Natural Frequencies and Relative Wind Speeds Over Which Vortex Shedding-Induced Vibrations Occur.

For the particular platform considered, the winds at the offshore site were in the range of 4 to 7 on the Beaufort scale. This translates to a wind speed range of 15 to 40 kt, which is similar to the range plotted in Figure 2. However, these winds were observed over extended time intervals at the platform installation site when the platform was barge-mounted and stationary in the water. The observed vortex-induced vibrations also were dependent upon the wind direction relative to the members which experienced damage. This directional effect is a result of the yaw angle dependence of the vibrations. At the larger yaw angles, greater than 30 to 40 degrees from normal incidence, the vibrations become less regular and are much reduced in level due to the irregularity and complexity of the vortex shedding. This behavior was in fact observed at the site.

Typical measured and predicted in-air amplitudes of displacement due to vortex shedding for a member of cylindrical cross-section are shown in Figure 1. The horizontal scale is the so-called "reduced damping" parameter (Griffin, 1985; Every, King and Griffin, 1982)

$$k_r = \frac{2m\delta}{\rho D^2}$$

where

δ = log decrement of structural damping;

ρ = fluid density (air), lb_m/ft³;

and again, m is the structural mass density (per unit length) and D is the cylinder diameter as defined previously.

An estimate was made of k_r for the platform members based on the properties and dimensions that were available. The estimated log decrement of the structural damping for the members in question,

was $\delta = 0.01$. Thus the reduced damping k_r is of the order $k_r = 10$ or less, and reference to Figure 1 then gives a crossflow displacement amplitude of $Y = \pm 0.3D$ or somewhat greater, depending on the actual value of the structural damping. Visual observations of the vibrations of the damaged X-frame platform members estimated the amplitudes of oscillation to be of the order of $\pm 1D$ and to be in the general form of breathing or crossflow oscillations normal to the plane of the X-frame when the relative orientations of the barge-mounted platform and the incident wind were aligned in the appropriate manner. These are precisely the vortex-induced vibrations which are likely to cause the most severe problems.

Thus it is likely that sustained, large-amplitude vibrations due to wind-induced vortex shedding were present and of sufficient duration at the offshore installation site to cause the observed damage to the platform members.

The expected amplitudes of displacement are sufficient to cause appreciable amplification of the aerodynamic drag on the cylindrical members. It is at the higher amplitudes of displacement which sometimes are encountered in air, as seen in Figure 1, and which are common in water that amplifications of the force levels well beyond those of an effectively stationary bluff object are encountered. The drag coefficient for the platform members is likely to be in the range $C_D = 1.3$ to 1.6 at the expected displacement amplitudes, which is an appreciable amplification from the drag ($C_D = 1.0$ to 1.2) on a cylindrical member that is restrained from oscillating.

The prediction of fatigue life is a complex problem and is not very well understood for structural members such as those under consideration here. The fatigue of a member undergoing bending is difficult to predict, but it is generally recognized that steel has a stress endurance limit which limits the safe survival time of a member. For an infinite number of bending cycles the endurance limit of stainless steel, for example, is approximately one-half the yield stress.

The damage to the platform was postulated to be stress-related fatigue failure, and this cause of damage was used to reinforce the vortex shedding postulation. The structural properties and parameters of the members and the in situ wind environment which the platform experienced provide further evidence that wind-induced vortex shedding caused large amplitude vibrations of sufficient magnitude and duration to cause the observed fatigue failures.

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Ice-Structure Interaction

Principal Investigators: Dr. S. Shyam Sunder
Dr. Jerome J. Connor
Massachusetts Institute of Technology
Department of Civil Engineering
Cambridge, MA 02139

Objective: To investigate using numerical models the mechanics of deformation and progressive failure in ice for the purpose of predicting global forces and local pressures generated on offshore structures proposed for deployment in the Arctic.

The extraction of hydrocarbon resources from the Arctic in an economical and safe manner poses many technical challenges to offshore engineering. At the root of these problems is the severe environment created by perennial ice features that impart global forces and local pressures on structures that are several times greater than those from waves in non-Arctic environments. Typically, two levels of ice loading are considered for design purposes. Global ice loads govern the overall structural geometry and dimensions as well as the foundation design, while local ice pressures dictate wall thicknesses and local framing, and may govern structural cost. It is widely recognized that significant uncertainties exist in current ice load models and that some design loads may be overestimated by an order of magnitude. Research is necessary to quantify the uncertainties in ice loads and to develop improved load prediction models for the safe and economical design of structures.

Uncertainties in existing ice load models arise primarily from five sources which include incomplete knowledge of the mechanical behavior of ice, including temperature and fracture effects; empiricism in existing theoretical models resulting from the use of approximate analysis methods; inadequate modeling of the contact forces at the ice-structure interface; neglecting the effect of scale/size on material strength; and not accounting for the finiteness of environmental and other forces driving the ice features.

In order to quantify these uncertainties and better predict global and local ice loads, numerical models are necessary for computer simulation of ice-structure interaction processes. In contrast to analytical methods, such models can realistically simulate the interaction accounting for spatial-temporal variability in the mechanical behavior of ice and for multiple modes of failure in ice. This project is concerned with the development and application of numerical models for quantifying ice-structure interaction processes. Three major areas of study are involved: (a) the development of generalized constitutive theories for characterizing deformation by flow, distributed cracking, and localized crack propagation in ice; (b) the development of finite element methods of analysis to account for nonlinearly viscoelastic flow and smeared crack models of ice; and (c) the numerical simulation of ice-structure interaction processes for ice sheets indenting rigid cylindrical structures.

A key aspect in the development of constitutive models is the need for accurate and consistent experimental data on ice. While currently available data is in many cases sufficient to postulate approximate constitutive models, the numerical simulations can help establish the importance of more extensive experimentation in quantifying ice-structure interaction processes.

Significant progress has been made in the description of ice deformation and failure under "break-out" or creep conditions, characteristic of the winter season. In particular, the problem of indentation in the creeping mode for wide structures in the Arctic nearshore zone has been extensively studied with newly developed numerical simulation models. Advanced constitutive descriptions of three-dimensional viscoelastic flow as well as distributed and local cracking have been developed. Current work is attempting to numerically simulate the formation and propagation of cracks in viscoelastically flowing ice. This progress is summarized in what follows.

A multi-axial differential flow law has been developed to model the elastic, transient, and steady flow in ice. Flow (or creep) is modeled in terms of nonlinear deformation-rate mechanisms: the first mechanism governs the transient deformation-rate (creep) which decays to zero as both an elastic back stress

and a drag stress measure increase asymptotically; the second mechanism, which is modeled in terms of the well-known power law, governs the viscous deformation-rate. The evolution of the back or rest stress contributes to kinematic hardening, while that of the drag stress contributes to isotropic hardening. The uniaxial model satisfies the dimensional requirements identified by M.F. Ashby and P. Duval, and also predicts the correspondence between creep and constant strain-rate response observed experimentally by M. Mellor and D.M. Cole.

The uniaxial model contains a total of six parameters that can be determined from conventional experimental testing methods. The model has been verified against the comprehensive creep data of T.H. Jacka, shown in Figure 1, as well as the data of N.K. Sinha. Predictions of the ratio of transient strain to total strain qualitatively agree with those of Sinha's model if grain size effects are taken into account. In consistency with the incompressible flow of glacier ice, the model predicts pressure-insensitive behavior under conventional triaxial loading conditions.

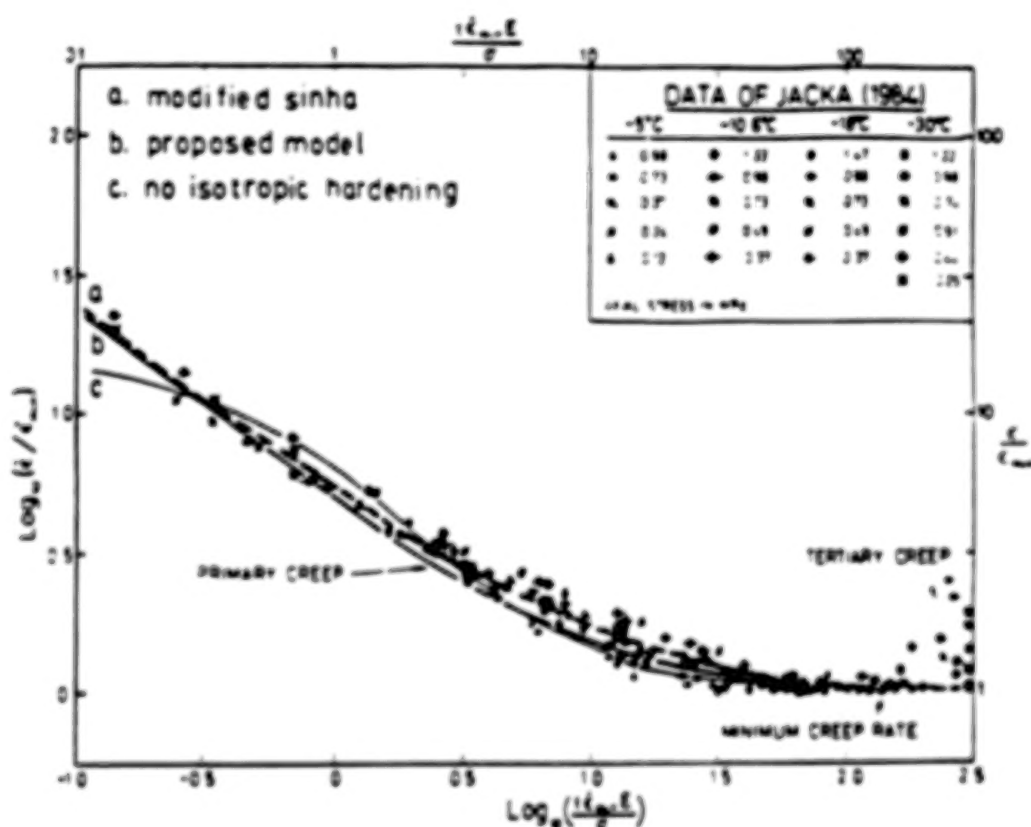


Figure 1 — Dimensionless Strain Rate Versus Dimensionless Time for Isotropic Polycrystalline Ice (after Shyam Sunder and Wu 1988. A Multiaxial Differential Flow Law for Polycrystalline Ice, *Cold Regions Science and Technology*, Submitted for Publication).

At low rates of loading, ice is a purely "ductile" material and its behavior can be characterized with flow theory. However, as the rate of loading is increased cracks can form in ice. Under tensile loading, the first crack which forms propagates in an unstable manner in ice with large grain sizes and at moderate to high rates of loading. These conditions are representative of most engineering applications. Consequently, the stress at which the first crack forms defines the tensile strength of ice. On the other hand, the first crack which forms under compressive loading is stable and has been linked to the yield point phenomenon in ice. The material can sustain additional compressive stress prior to reaching its ultimate strength.

The link between first crack formation under tensile and compressive states of loading has been investigated. This is based on the limiting tensile strain, i.e., the strain at which a tensile specimen fails at a given rate of loading. It has been shown that under compressive loading the first crack forms when the lateral tensile strain resulting from the Poisson effect and incompressibility condition of flow equals the limiting tensile strain. The predicted time to formation of the first crack in ice under compressive loading agrees well with the experimental data of L. W. Gold as shown in Figure 2. Consequently, it has been possible to establish a definite relationship between tensile strength and yield in compression. In particular, this suggests that for an elastic material the ratio of the tensile strength to the yield stress in compression must equal the Poisson's ratio. This prediction is supported by experimental evidence on ice under tension-compression states of stress. Using the more general relationship to account for flow in ice, a rate sensitive yield/failure surface has been developed using the Drucker-Prager formulation.

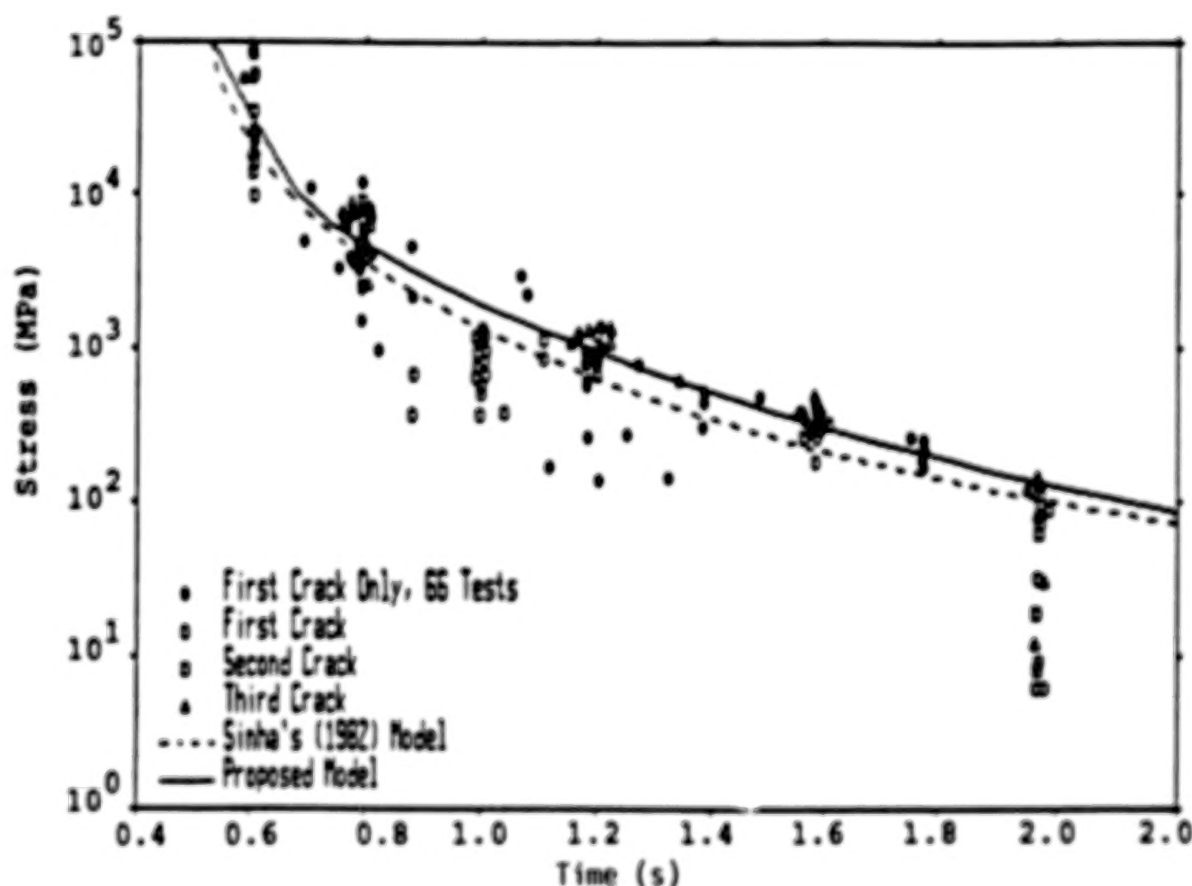


Figure 2 — Formation of First Cracks During Uniaxial Compressive Creep Tests.

Knowledge of tensile strength is important, but by no means sufficient to characterize the tensile fracture of ice. A toughness or energy measure is necessary to quantify the stress at which a pre-existing crack will propagate. Linear elastic fracture mechanics has been applied by several investigators for determining the fracture toughness of ice. The general testing methodology, particularly the selection of specimen sizes, has been borrowed from metal plasticity. However, ice is very different from metals. Metals are highly ductile and the plastic zone surrounding the crack tip absorbs most of the energy, which can be more than 1000 times the energy required for creating the new surfaces as the crack advances. On the other hand, ice displays both "quasi-brittle" and "creep" behavior depending on the temperature and rate of loading. In ideally brittle materials, e.g., glass, almost all the energy is consumed in creating the new surfaces with negligible energy dissipation in the "process" zone ahead of the crack tip. The stresses near the crack tip can approach the theoretical tensile strength of the material.

The research effort has been concerned with understanding the toughening mechanisms at high rates of loading and low temperatures where ice behaves as a "quasi-brittle" material. In such materials, the process zone is localized on a plane and does not resemble the kidney shaped plastic zone of metals. The process zone behavior is characterized in terms of a stress-separation relationship. Predictions of the process zone size and critical crack tip opening displacement have been made. The latter predictions agree with the limited experimental evidence currently available for ice. It has been shown that process zone size estimates based on the stress-separation model are significantly greater than those from the formulation used in metal plasticity or for materials obeying a power law of creep. Using the stress-separation model in conjunction with the tensile flow law and strength model, an objective energy release rate criterion has been developed for numerically simulating tensile cracking in ice based on the blunt crack band theory.

Ice displays purely ductile, purely brittle or combined behavior depending upon the temperature and conditions of loading. The phenomenon of distributed cracking associated with the formation and stable growth of cracks governs the ductile-to-brittle transition or purely brittle behavior of ice. The phenomenon, sometimes termed damage, controls the process of failure of quasi-brittle materials such as ice prior to localization of fracture (formation and propagation of a single, large crack). Distributed cracking weakens the material; under constant strain rate loading this contributes to "strain-softening" and under constant stress loading to "tertiary" creep. Consequently, the ultimate strength and post-peak response of ice is generally governed by damage. Damage processes are particularly significant when the state of stress involves compression.

Research has been initiated to understand and characterize damage processes and the interaction mechanisms between damage and flow in ice. The study is investigating the influence of confining pressure on damage during constant strain rate loading and under conventional triaxial states of stress. The application of a low to moderate level of confining pressure tends to suppress cracking, which in turn allows a higher shear/distortional stress to be sustained. As the confining pressure is further increased, the material displays pressure insensitive ductile flow, and eventually at very high confining pressures, ice may undergo a change in phase or morphology. This research seeks to theoretically characterize the rate-sensitive evolution of damage during deformation by viscoelastic flow with the preliminary results shown in Figure 3.

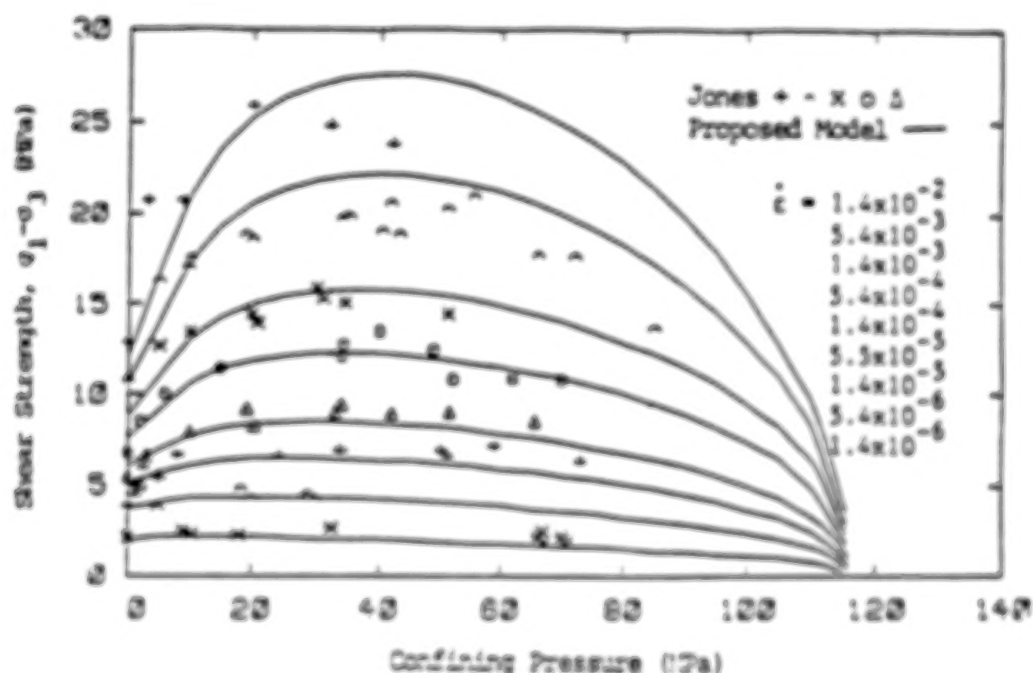


Figure 3 — Shear Strength Versus Confining Pressure for Freshwater Ice at -12°C (after Wu and Shyam Sunder 1988. A Rate and Pressure Sensitive Damage Model for Polycrystalline Ice, In Preparation).

A finite element method of analysis has been developed for the nonlinear viscoelastic and anisotropic behavior of ice based on a weighted equilibrium-rate formulation. The rate formulation allows realistic simulation of the spatial-temporal variability in the strain rate field, and no empirical definition of an average strain rate measure is necessary as in ice load models derived from plasticity theory. The isotropic and kinematically hardening constitutive model of flow consists of stiff differential equations that pose serious stability and efficiency limitations. An efficient explicit-implicit numerical integration algorithm based on a gradient (Newton-Raphson) technique has been developed which enables fast convergence in problems where inelastic deformations dominate. Variable interface conditions between the ice feature and the structure can be simulated to bound the effects of interface bond or friction.

Numerical simulation studies have been performed under plane stress conditions to study the sea ice indentation problem for wide structures under steady flow conditions. Creep is the predominant mode of deformation for artificial islands in the Arctic nearshore region during "breakout" and/or steady indentation conditions occurring during winter. Further, stresses, strains and strain rates resulting from creep are necessary to predict the growth and propagation of localized and distributed cracks when rate effects influence fracture behavior. The numerical simulations quantify the effect of (i) material model, i.e., isotropic versus transversely isotropic; (ii) natural variability in material parameters; (iii) approximate versus "exact" methods of analysis and the ability of each to model interface adfreeze and friction as well as spatial-temporal variability in the strain rate field; and (iv) grounded rubble pile or accreted ice foot. Theoretical predictions of pressure-area curves used in the design of structural components have been developed and are shown in Figure 4.

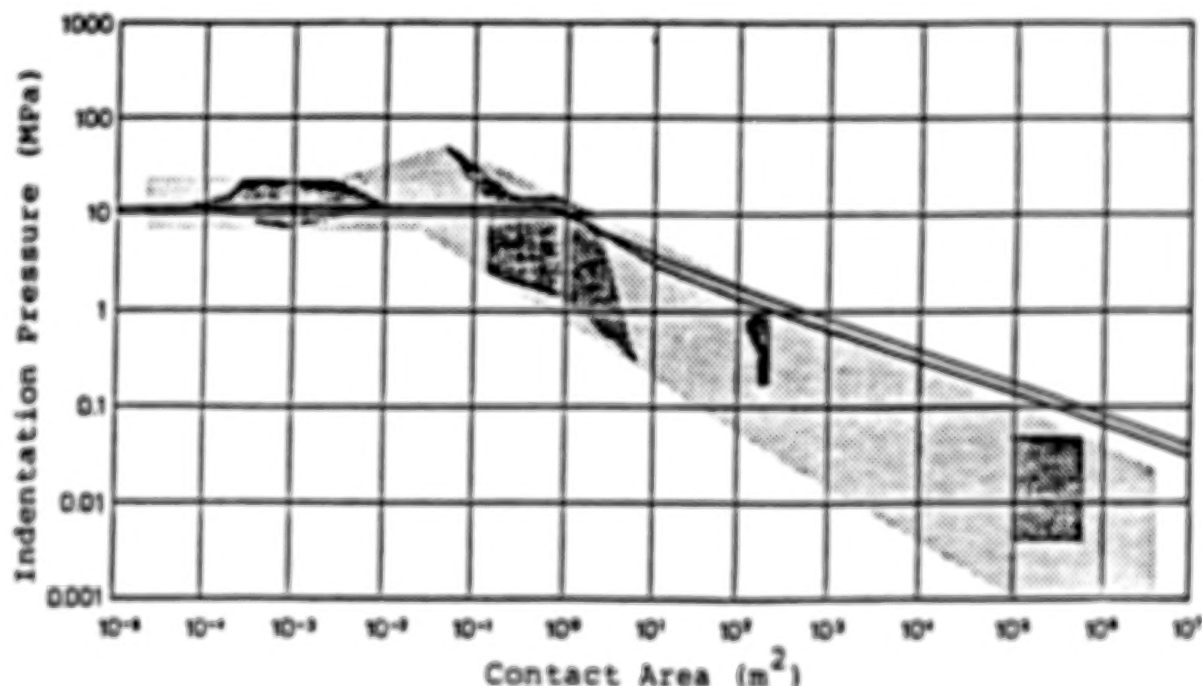


Figure 4 — Pressure-Area Curve.

The primary focus of current research is concerned with modeling quasi-static propagation of discrete tensile cracks and the development of distributed cracking or "damage" zones under compressive loading. The numerical model under development is a generalization of the finite element formulation to account for tensile cracks and damage zones. Two of the more common approaches for studying tensile cracking are the discrete crack models which follow individual discrete cracks between elements and the smeared crack models which treat the gross (smeared) effects of cracks in an element. The latter approach is computationally far more efficient and convenient, and eliminates the need for remeshing as the crack advances. An added advantage is that smeared crack models can be extended easily to allow for

an objective energy release rate criterion for propagation of discrete tensile cracks. This criterion helps modify a "tensile strength" based propagation criterion, which produces results that may be sensitive to the particular choice of a finite element mesh size, to a "toughness" or "energy" based criterion that governs the fracture behavior of materials. The resulting theory is called the blunt crack theory. The smeared crack model and its variation, the blunt crack band theory, is known to provide accurate estimates of overall material response, although details of individual crack growth patterns are known less precisely. But in applications where the primary objective is to predict the total loads transmitted by an ice feature, as is the case for ice, such details are of less importance.

These crack models will be developed and implemented in conjunction with the rate-sensitive multiaxial failure criterion for compressive yield/tensile fracture strength. Generalization of the finite element formulation for modeling the development of damage zones will require the development and implementation of a numerical algorithm for simulating strain-softening as well as the constitutive theory of rate-sensitive damage.

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Mechanical Properties of Saline Ice

Principal Investigator: Dr. Erland M. Schulson
Ice Research Laboratory
Thayer School of Engineering
Dartmouth College
Hanover, NH 03755

Objective: To determine the relationship between the internal structure and the mechanical properties of saline ice and, through this work, to reveal the mechanisms controlling strength and fracture.

In view of the impediment imposed by sea ice to the exploration and development of mineral resources in the offshore Arctic, an experimental program is in progress to explore in a systematic manner the mechanical properties of the material. Measurements to date have been made of both uniaxial tensile and compressive strength and of fracture toughness, and variables have included grain size, orientation, loading and strain rates and temperature. Measurements are soon to be made of the coefficient of fracture of ice on ice, and the important variable, stress state, will be introduced once the multiaxial loading system arrives in the laboratory in June of this year.

Saline ice is a composite of pure ice, pockets of brine and gas and (if below -22°C) particles of salt. Its mechanical properties, therefore, are controlled in part by the properties of pure ice and by the influence of the other phases. For this reason, both saline ice and fresh-water ice are being investigated in parallel. The test materials originate from the laboratory and from the field. Saline ice from the laboratory, grown under conditions which simulate those which occur in nature, possesses both structure and properties typical of first-year sea ice. (Kuehn, et al., 1988).

Recent results have shown that the brittle compressive strength, σ_c , of ice is determined by the grain size, d , the fracture toughness, K_{Ic} , and the degree, Z , to which microcracks interact. In addition, and most importantly, the strength is affected by the frictional resistance to sliding, m , of one face of a shear crack against the other. Quantitatively the relationship may be expressed as follows (Schulson 1987):

$$\sigma_c = \frac{Z K_{Ic} d^{1/2}}{(1 + \mu^2)^{1/2} - \mu}$$

Confirming this expression are the experimental data in Figure 1, obtained for equiaxed and randomly oriented fresh-water ice. Both the large increase in strength with decrease in temperature and the reduction in strength with increase in strain rate can be quantitatively explained in terms of the effects of temperature and sliding velocity on m (Schulson 1987).

The tensile strength of laboratory-grown columnar saline ice and of first-year columnar sea ice harvested in April 1983 and in November 1984 from Prudhoe Bay has been measured at -10°C at two strain rates (10^{-3} and 10^{-5}s^{-1}) and in two orientations (through-thickness or vertical and in-plane or horizontal). The results, Figure 2, (Kuehn et al. 1988) show that at both rates the through-thickness strength is 3 to 4 times greater than the in-plane strength, and that for both orientations the strength at the higher rate is only slightly ($\sim 25\%$) greater than that at the lower rate. Also, the results show that the strengths of the laboratory-grown and of the field ice are essentially indistinguishable. The last point is substantiated from the results of compression tests on the same materials, and reflects the similarity in structure and salinity of the two kinds of saline ice (Kuehn, et al., 1988).

The tensile strength of pre-cracked ice when rapidly strained at 10^{-3}s^{-1} is controlled by the propagation of the pre-existing cracks, provided that the cracks exceed a critical size and are sharp (Schulson, Hoxie and Nixon, 1988). When the cracks are short, or when they are long but blunted through creep deformation at the crack tip, the strength is controlled by the nucleation of new cracks. The critical size, $2c_c$, is given by the relationship:

$$2c_c = \left(\frac{\pi}{2} \right) \left(\frac{K_{Ic}}{\sigma_c + k d^{1/2}} \right)^2$$

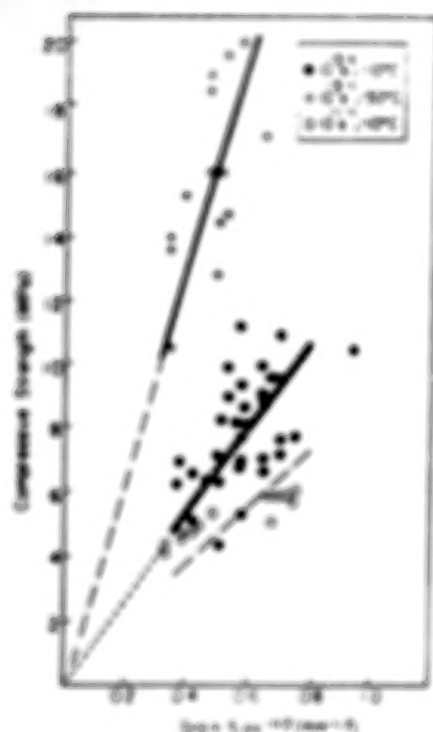


Figure 1 — Uniaxial Compressive Fracture Strength of Ice as Versus Grain Size (d) , as a Function of Temperature and Strain Rate.

At -10°C , $\sigma_y = 0.51 \text{ MPa}$ and $k = 0.03 \text{ MPa} \cdot \text{m}^{1/2}$ at $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$; $K_n = 0.058 + 0.041d^{1/2} \text{ MPa} \cdot \text{m}^{1/2}$ for d in mm.

Important implications of these results are that pre-existing cracks do not necessarily weaken ice, that the thermal-mechanical history of a cracked ice sheet is a significant factor in determining its mechanical behavior, and that pores per se (which concentrate stress much less than cracks) cannot be strength limiting features of natural ice.

The ductile to brittle transition in ice under compressive loading is frequently expressed in terms of the deformation rate. At -10°C , for instance, the transition is noted to occur upon raising the strain rate above 10^{-3} s^{-1} . If the ice is confined, then the transition occurs at a higher rate, depending upon the confining pressure. In addition to rate and confinement, however, recent work (Schulson, Kuehn and Nixon 1988) has revealed that prestrain is important.

Experiments were performed on granular fresh-water ice prepared in the laboratory and on columnar salt-water ice obtained from both the field and the laboratory. Cylindrical specimens of both types of ice were prestrained at -10°C by shortening 3.5% at 10^{-3} s^{-1} (i.e., within the ductile regime). Subsequently, they were strained again, but at rates $\geq 10^{-3} \text{ s}^{-1}$.

In every case, including vertically oriented sea ice and horizontally oriented saline (i.e., laboratory grown) ice, the material was ductile when re-strained at 10^{-3} s^{-1} . Additional shortenings of 4.5% were imparted without causing the specimens to collapse. When re-strained at 10^{-3} s^{-1} , both the fresh-water ice and the horizontally oriented saline ice collapsed after an additional shortening of about 0.5%.

The results show that prestrain raises the strain rate at which the brittle to ductile transition occurs under compression, and that the effect is limited to neither one type of ice nor to one orientation of columnar sea ice.

Again, an implication of the test results is that the mechanical history of an ice sheet may be a significant factor when considering its behavior.

Tensile tests have been performed on notched and unnotched cylindrical samples of randomly oriented polycrystalline ice of controlled grain size (between 2.2 and 7.3 mm) at loading rates of 100 Fz

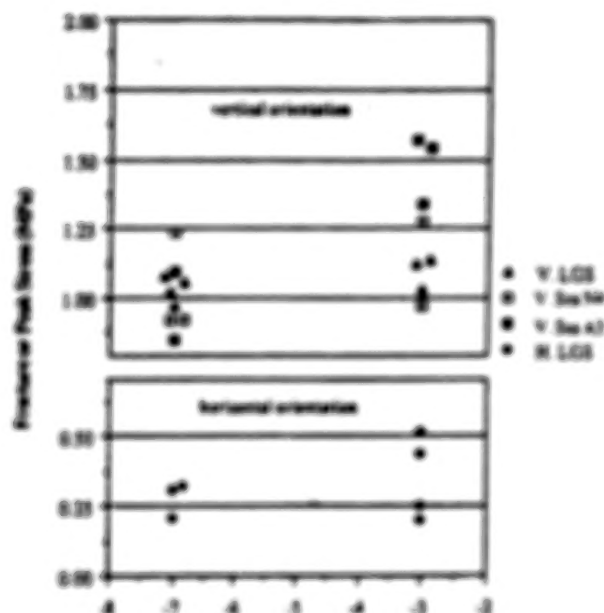


Figure 2 — Saline Uniaxial Tension Test Data. Tests Were Performed at -10°C , N4 and A3 Means Respectively, Ice Harvested in November 1984 and April 1983.

s² and at a temperature of -10°C. In the notched samples, the notch root diameter was 80% of the base diameter. A notch strengthening effect (Nixon and Schulson, 1988) was observed in the large grained ice, with fracture stresses being up to 50% higher than for unnotched samples of the same grain size. This notch strengthening effect diminished as grain size decreased, disappearing at a grain size of ~ 3 mm.

A model has been developed which explains the notch strengthening effect in terms of the triaxial stress constraint at the notch root. The triaxial constraint results in a change in the controlling mechanism of fracture from crack initiation in the notched samples to crack propagation in the unnotched samples.

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Inspectability of Tension Leg Platform Tendons

Principal Investigator: John E. Halkyard
Arctec Offshore Corporation
Escondido, California 92025

Objective: To validate a theoretical ultrasonic model for predicting the minimum detectable flaw size in specific components.

The "Inspectability of Tension Leg Platform Tendons" program is a multi-phase study to investigate tension leg platform (TLP) tendon designs and how various parameters affect their inspectability. During the first phase of the program, non-destructive evaluation (NDE) methods were evaluated for their applicability to in-service tendon inspection.

The requirement for inspection was examined during this phase of the study from the standpoint of tendon damage tolerance under various loading and other scenarios. The results indicated that in relatively benign fatigue environments and with suitable designs, the frequency of in place inspection could be very low - even beyond the intended service life of the structure. In very severe environments the inspection frequency could be less than the service life, however in any event design specific damage tolerance analysis is required to determine a suitable inspection interval. The analysis indicated a desirable threshold for crack detection in the range of 4-8 mm deep (Bossi, et al.).

Ultrasonic NDE was found to be the most viable method for the conditions, designs and inspection needs. An ultrasonic model was developed for non-destructive evaluation in complex geometries. The model was a mathematical simulation of the ultrasonic inspection, dependent upon the geometry under test for threaded connectors in tension leg platform design.

The second phase of the study used materials and geometries of interest to experimentally test the model for predicting the acoustic response from notch defects and fatigue cracks. This program investigated factors that influence ultrasonic inspection defect detectability and sizing such as the material, coatings, and marine growth. Welded coupling design was also considered. The correlation of notch defect signal response to fatigue crack signal response was also evaluated in the program. Table 1 lists the specimens tested during this program.

The ultrasonic model which was validated by this program is given by:

$$p/p_t = C_1 R^2 e^{-\alpha \frac{S_s S_r}{d \lambda^2}} \quad (1)$$

where

- p = Measured echo response pressure amplitude.
- p_t = Transmitted pressure pulse amplitude.
- R = Reflection coefficient (equal 1.0 if beam path does not include reflection from a wall).
- α = Attenuation coefficient.
- d = Nominal distance between source (transducer) and reflection (crack).
- S_s = Area of acoustic source.
- S_r = Area of reflector.
- λ = Acoustic wavelength.
- C_1 = Transmissivity coefficient between water and steel.

Equation (1) was derived from Kirchhoff diffraction theory considerations. This theoretical model assumes that the defect is planar lying in a plane perpendicular to the ultrasonic beam and that the beam is larger in diameter than the defect. Under these circumstances the energy reflected from the defect will return to the transducer and will be proportional to the defect size. Figure 1 demonstrates this condition.

Table 1 — Test Specimens

Specimen	Purpose	Dimensions	Material	Comment
1	Retempering	8 x 8 x 3	2 1/8 Cr-Mn(1)	
2	Retempering	8 x 8 x 3	4140	
3	Retempering	8 x 8 x 3	4340	
4	Flaw Size and Location Effects	20 x 6 x 2.5	2 1/8 Cr-Mn	Rare Metal
5	Flaw Size and Location Effects	20 x 6 x 2.5	2 1/8 Cr-Mn	Epoxy Coated
6	Same as 4 and 5	20 x 6 x 1 3/8	2 1/8 Cr-Mn	Tool Joint Dimensions
	weld effects	15 x 15 x 1	4140 [X]	Charpy
	weld effects	15 x 15 x 1	4140	Compos
6A	Thread Effects	20 x 6 x 2.5	2 1/8 Cr-Mn	Reduced Thread
6B	Thread Effects	20 x 6 x 1 3/8	2 1/8 Cr-Mn	API V Thread
7	Marine Growth	20 x 6 x 2.5	4340 41 Flare Sprayed	Fouled and water Jet Cleaned
8	Marine Growth	20 x 6 x 2.5	4340 41 Flare Sprayed	Fouled and Scraped/Brushed
13	EDM notch versus fatigue crack	20 x 6 x 1	2 1/8 Cr-Mn	EDM Notch
14	Same as above	20 x 6 x 1	2 1/8 Cr-Mn	Fatigue cracked
15	Same as above	20 x 6 x 1	2 1/8 Cr-Mn	Fatigue cracked
16	Same as above	20 x 6 x 1	2 1/8 Cr-Mn	Fatigue cracked
16A	Same as above	20 x 6 x 2.5	2 1/8 Cr-Mn	Fatigue crack to thread
16B	Same as above	20 x 6 x 2.5	2 1/8 Cr-Mn	Fatigue crack to thread

Notes:

1. 2 1/8 Cr-Mn is designation for API 5A 367 Class 1 Steel
2. 4170 is Nippon proprietary steel similar to 4140
3. All alloy steel was heat treated to attain a minimum 50 Rc as quenched hardness, and tempered to a minimum 30 Rc.

The model includes terms for the transmission of ultrasound across a boundary, reflection at a surface, attenuation over a path length and response from a reflector based on source and reflector size and beam spread. Values for the terms in this model can be found in the literature, Krautkramer (1983).



Figure 1 — Example of Ultrasonic Reflection From a Defect Proportional to Defect Size.

The general geometric configurations of interest for tension leg platform design are shown in Figures 2 and 3. Figure 2 shows the threaded connector and Figure 3 the welded connector. The growth of fatigue cracks at roots of threads or in the weld zone will not form the simple geometry of Figure 1.

Instead, the crack and edge of the part will form a type of corner reflector. It might be expected that the corner trap could be modeled as a planar crack of equivalent size to the shadowing effect of the beam as shown in Figure 4. In cases where the beam angle is not 45° and/or the fatigue crack is not perpendicular to the surface the reflectivity of the corner is altered from that predicted by strict geometric raytracing consideration. A beam will nevertheless be returned to the transmitting transducer. The actual inspection of the tension leg connector therefore differs from the theoretical model in terms of the ultrasonic beam and orientation to the defect.

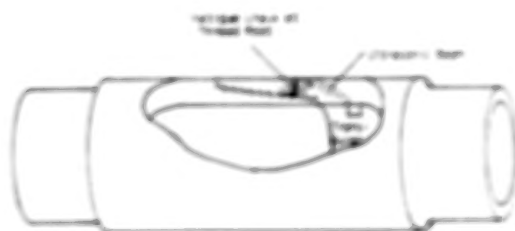


Figure 2 — Threaded Connector Example of Tension Leg Tendons With Fatigue Crack at Root of Thread.

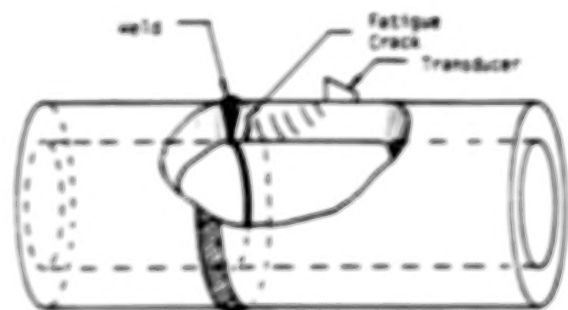


Figure 3 — Welded Connector Example of Tension Leg Tendon With Fatigue Crack in the Heat Affected Zone of Weld.

For actual inspections, transverse waves are preferred. Studies show that longitudinal waves tend to have a lower response from surface breaking cracks than transverse waves, Kapranos (1984). Also, when longitudinal waves are used in angle beam techniques, transverse waves will also be present which can generate confusing echo responses. In complex geometries, such as connectors, it is preferred to use beam angles of transverse waves such that the longitudinal waves are not present in the initially injected beam. This minimizes the number of confusing signals from multiple modes of ultrasound. Note, both longitudinal and transverse waves can be generated at reflection and refraction interfaces with relative magnitudes dependent upon the incident beam mode and signal. Transverse waves are also preferred because the wavelength is smaller than the longitudinal waves which is important in the detection of small defects.

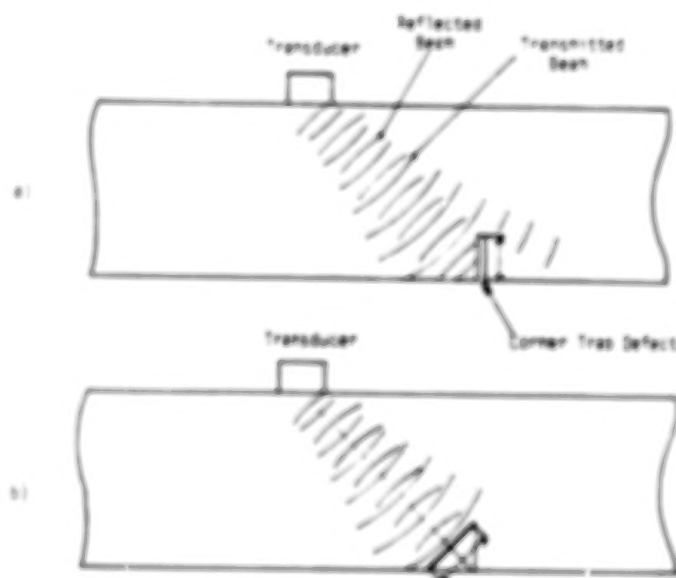


Figure 4 — Corner Trap Reflection a) Beam Configuration. b) Equivalent Sized Planar Reflector When Beam Is at 45° .

Other models are under development and measurements are being made of their parameters [Chapman (1981), Coffey (1983), Thompson (1983)]. In the future much better predictions than the model of equation (1) will be developed. Within the scope of the current program, however, the equation (1) model was used to gain insight into the ultrasonic inspection problem.

The amplitude response from defects, calculated from this theoretical model is useful for predicting conditions which will allow ultrasonic inspections. Other factors which influence inspectability are also important. These include the effects of material selection and coatings on the material and the presence of marine growth and marine growth removal methods. These factors will influence the predicted response from the model. The model predicts the amplitude response as a function of defect size. Defect sizing accuracy is an important element in inspectability. The amplitude response from defects has traditionally been used for crack size estimation in most ultrasonic inspection efforts. It is likewise well recognized that considerable deviations from expected response as a function of size in standards versus real defects exist. Factors such as defect type, shape orientation and surface condition in addition to size will influence the amplitude response (Rogerson).

The second phase effort involved experimental tests of ultrasonic response from defects to correlate to the model.

The experimental technique for the basic tests used conventional ultrasonic equipment. Measurements of ultrasonic response were taken in an immersion tank with a manual, vernier driven scanner. Figure 5 illustrates the setup used. The pulser/receiver system consists of a Metrotek 215 pulser and 101A receiver. These modules have fairly standard performance for the industry and are used in many modular component systems. The pulser applies a high voltage spike to the transducer. The transducers are common piezoelectric crystal materials. The primary set selected for the study is made of lightly damped lead zirconate (PZT). This transducer gave a relatively high response with a moderate bandwidth. Transducers of lead metaniobate, highly damped are also available. These transducers have a broad bandwidth and less noise than the PZT, but have a weaker response. The transducer crystals were cut to have a resonance at a specified frequency; 1 MHz, 2.25 MHz, and 5 MHz primarily. Used with the MP 215 pulser, however, the ultrasonic beam generated was composed of a frequency spectrum about the center frequency. This "real world" behavior of the transducer/pulser performance differs from the theoretical approach of the model where the calculations were based on specific frequencies values. The measurements were intentionally made using the "real world" performance characteristics rather than developing specialized ultrasonic systems for theoretical verification measurements. This approach has greater meaning for future implementation of the technique in spite of reduced accuracy from the model representation.

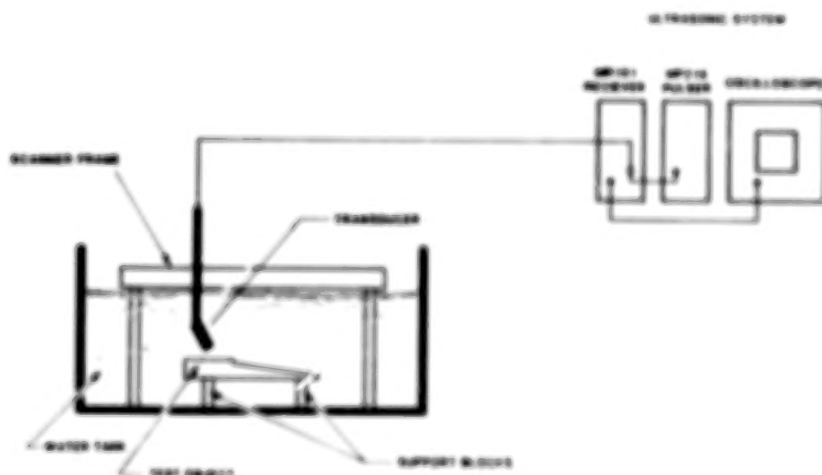
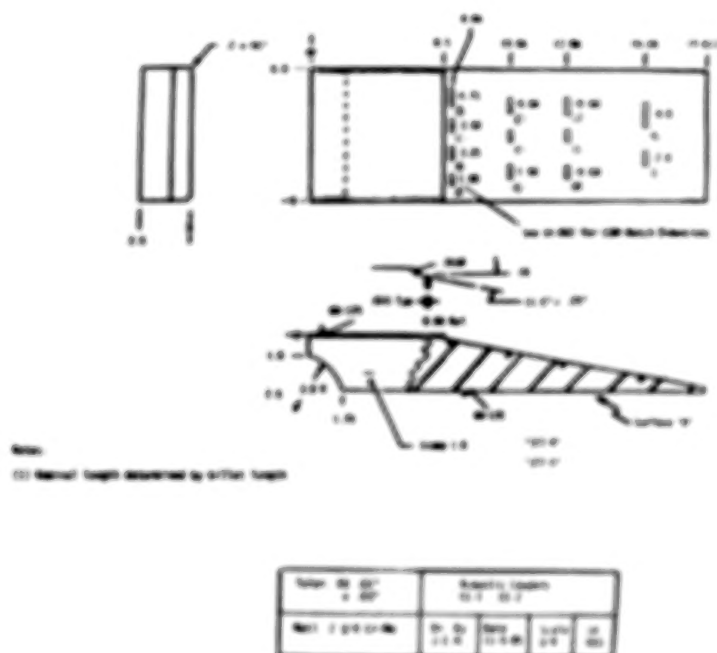


Figure 5 — Experimental Setup.

Conclusions

Acoustic response measurements from notches were made on specimens 4, 5, and 6 (Table 1). Figure 6 shows the configuration for specimens 4 and 5. Specimen 4 was bare while specimen 5 had an epoxy coating. Figures 7 and 8 are two representative figures of the acoustic response measurements. The calculated response shows a higher slope than the measured. The measured response shows a leveling off of response with notch size. The conclusion is that the model can be used for order of magnitude estimates of response but not for accurate prediction of notch sizes. The predicted 0.001 sensitivity proved to be conservative. All notches in the test samples were detected.



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Mechanical Properties of Multi-Year Sea Ice

Principal Investigator: Jacqueline Richter-Menge
U.S. Army Cold Region Research and Engineering Laboratory
Hanover, N.H. 03755-1290

Objective: To conduct ice structure analysis and to examine systematically the engineering properties of ice samples taken from multi-year ridges.

Interest in the properties of multi-year ridges stems from the fact that these ridges are the most frequently encountered, massive ice features in exposed areas of Beaufort and Chukchi Seas. Deep-water oil platforms constructed in this area of the arctic must be designed, therefore, to withstand the impact of a multi-year ridge.

Phase I and Phase II of the program involved field sampling in the southern Beaufort Sea. The Phase I field program was conducted in April 1981 and involved the sampling of 10 different pressure ridges. A continuous, vertical multi-year ridge core was also specifically obtained for detailed structural analysis. A total of 220 unconfined uniaxial constant-strain-rate compression tests were performed on the vertically cored ice samples from the 10 ridges. The preliminary ice structure analysis of these test specimens indicated that the main factor contributing to large variations in the test results was associated with the extreme local variability of ice structure within a ridge. It became apparent that a complete and useful analysis of the multi-year ridge ice property test data would require a thorough structural interpretation of each test sample.

Additional multi-year ice from four ridges was collected in April 1982 for the Phase II tests. These field samples included horizontally and vertically cored ice samples taken in close proximity to one another. The matched pairs were tested in unconfined, uniaxial constant-strain-rate compression to investigate the effect of sample orientation on the test results. The remaining vertical ice samples were used in additional unconfined compression tests and in confined constant-strain-rate compression, constant-strain-rate tension, and constant load compression tests. A total of 188 tests were done in Phase II. During the Phase II field program, a second vertically drilled continuous ridge core to augment the ice structure data obtained in Phase I was extracted. The complete set of results can be found in Richter-Menge and Perron (1988). The structural analysis of the ice samples tested in Phase I is presented in Richter-Menge et al. (1987). Discussions on the field sampling program and the test results and analyses for Phases I and II can be found in Cox et al. (1984, 1985, respectively).

The structural characteristics of the Phase II ridge test specimens were evaluated using the same techniques described in Richter-Menge et al. (1987). The ice type of each sample was described according to the multi-year pressure ridge ice structural classification scheme summarized in Table 1. Figure 1 shows a series of thin sections, photographed between crossed polarizers, that illustrates the principal structural characteristics of each ice type.

Table 1 — Structural Classification Scheme for Multi-Year Pressure Ridge Ice Samples.

Ice type	Code	Structural characteristics
Granular	I	Isotropic, equiaxed crystals
Columnar	II	Elongated, columnar grains
	IIA	Columnar sea ice with c-axis normal to growth direction; axm may or may not be aligned
Mixed	IIC	Columnar freshwater ice
	III	Combination of Types I and II
	IIIA	Largely Type II with granular veins
	IIIB	Largely Type I with inclusions of Type II ice (brecciated ice)

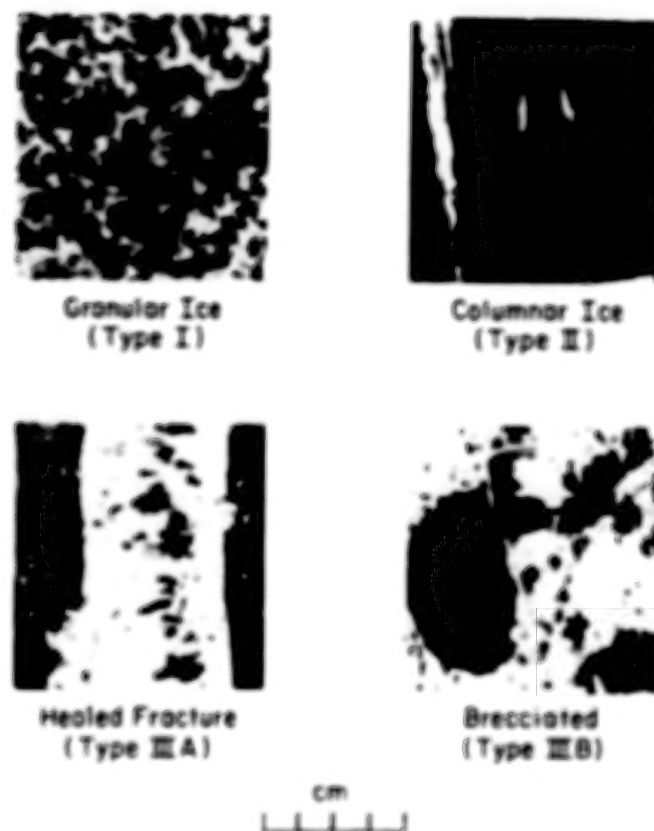


Figure 1 — Structural Characteristics of Multi-Year Ice Types.

Using petrographic analysis techniques, the mean angle between the crystallographic c-axes and the load direction (σ_z) and the degree of alignment of the c-axes ('spread') in samples that were classified as columnar were defined. These measurements were also made on large (≥ 10 cm) fragments of columnar ice in the mixed ice samples. In addition, measurements were made of the angle between the columns, or direction of elongation of the crystals, and the load (σ_z). In an undeformed sheet of first-year sea ice the crystals are elongated vertically ($\sigma_z = 0^\circ$), parallel to the growth direction of the sheet. The c-axes of these crystals are usually located in the horizontal plane of the ice sheet, normal to the elongation direction of the crystals. By observing the orientation of the crystallographic c-axes and the direction of elongation of the crystals in the ridge samples, we can determine the arrangement of some of the columnar fragments of first-year sea ice that have been incorporated into a ridge. The maximum, minimum, and mean grain sizes of the columnar and/or granular crystals were estimated for each sample.

The Phase II unconfined, uniaxial constant-strain-rate compression tests were done at two temperatures (-5 and -20°C) and two strain rates (10^{-3} and $10^{-4}/\text{s}$). The test parameters were chosen to complement the unconfined constant-strain-rate compression tests done in Phase I at the same temperature, but at strain rates of 10^{-3} and $10^{-4}/\text{s}$. Matched pairs of horizontally and vertically cored samples were tested at -5 and -20°C and a strain rate of $10^{-4}/\text{s}$ to determine the effect of sample orientation on the compressive strength of the multi-year ice. These samples were paired according to their location within the ridge. A summation is given of the percent granular, columnar, and mixed ice samples at each test condition in Phase I and II in Table 2. As noted in the Phase I ice structure analysis report (Richter-Menge et al., 1987), the most common ice type by far is the mixed columnar and granular ice. Columnar ice was the dominant ice type at only one Phase II test condition: -20°C and $10^{-4}/\text{s}$. The distribution of ice types is relatively consistent among all other test groups.

The compressive strength of the multi-year ridge samples is plotted against sample porosity and the structural classification is indicated for each test specimen in Figures 2a through d.

Table 2 — Summary of Percent Granular, Columnar, and Mixed Ice Samples at Each Phase I and Phase II Unconfined Compression Test Condition.

	-5°C				-20°C			
	10 ⁻¹ /s	10 ⁻²	10 ⁻³	10 ⁻⁴	10 ⁻¹	10 ⁻²	10 ⁻³	10 ⁻⁴
Granular	0	7	0	10	11	3	0	2
Columnar	22	25	16 (20)	19	11	20	56 (66)	30
Mixed	78	68	84 (80)	71	78	77	44 (34)	78
Total samples tested	9	69	19 (9)	71	9	41	25 (13)	41

() Vertically cored samples only.

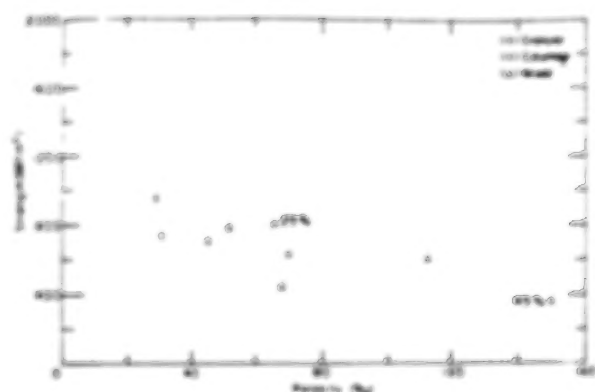


Figure 2a — Tests Conducted at 10% and -5° C.

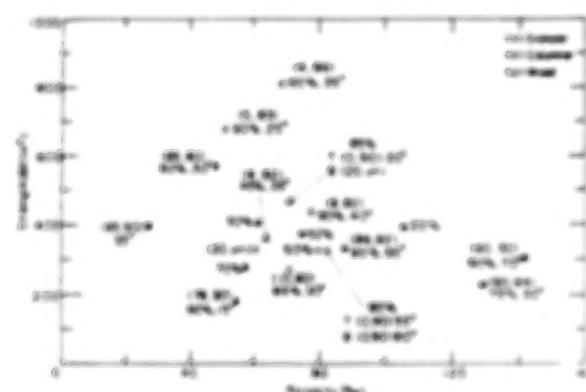


Figure 2b — Tests Conducted at 10% and -5° C.

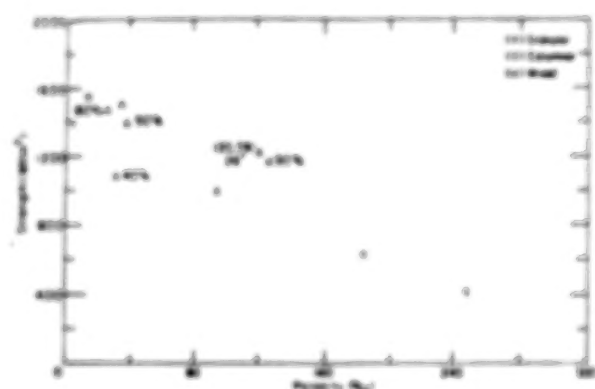


Figure 2c — Tests Conducted at 10% and -20° C.

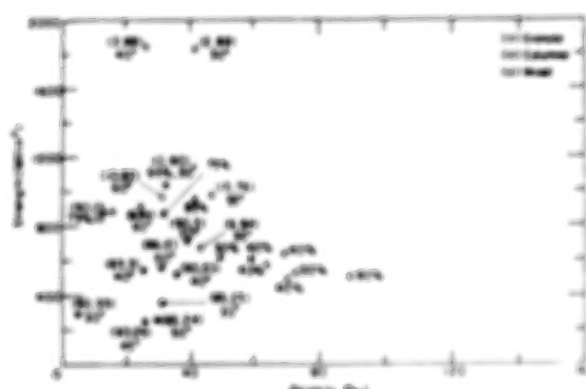


Figure 2d — Tests Conducted at 10% and -20° C.

Figure 2 — Unconfined, Constant-Strain-Rate Compressive Strength vs Porosity for All Phase II Ridge Ice Samples With the Structural Classification Indicated for Each Sample. Open Symbols = Vertically Cored Samples; Closed Symbols = Horizontally Cored Samples. Crystallographic Measurements Indicated Next to Each Sample: (σ12, σ1c), % Columnar, % Spread.

In general, the influence of ice structure and crystal orientation on the unconfined compressive strength of the Phase II samples is similar to that described for the Phase I ice samples in Richter-Menge et al. (1987). At a strain rate of 10^{-4} /s and temperature of -20°C (Figure 2d), the highest strength samples are composed of columnar ice with the direction of crystal elongation parallel to the load ($\sigma_z \leq 10^{\circ}$) and a relatively small degree of c-axis alignment ($< 50^{\circ}$). The mixed ice samples with a high percentage of columnar ice (80% or more) exhibit characteristics similar to the columnar ice samples. This is evident in the tests done at a strain rate of 10^{-4} /s and temperature of -5°C (Figure 2b). These mixed ice samples lie on the perimeter of the strength vs porosity bond. At all test conditions, 10^{-4} and 10^{-5} /s, there is a tendency for the compressive strength of the mixed and granular ice samples to decrease with an increase in porosity. The influence of grain size on the compressive strength of the ridge samples appears insignificant compared to the effects of crystal orientation and porosity.

The tests done on the matched pairs (Figures 2b and d) do indicate that the mean compressive strength of ice samples from a multi-year ridge is dependent on sample orientation. Vertically cored samples tend to give a higher mean strength than horizontally cored samples. The dependence of mean compressive strength on sample orientation can be explained by ice structure. The ice structure analysis of the ridges that we have sampled, including ridge C, suggests that most of the large columnar ice blocks in a multi-year ridge that was initially formed by compression lie in a near-horizontal position. At this orientation the direction of elongation of the crystals or the columns in these large ice blocks is near vertical. The columnar ice samples collected from vertical coring will therefore be loaded nearly parallel to the direction of crystal elongation ($\sigma_z = 0^{\circ}$). This is the hard fail direction in columnar ice. Horizontally cored columnar ridge samples tend to have an angle of 90° between the long columns and the applied load ($\sigma_z = 90^{\circ}$). Work by Peyton (1966) and Timco and Frederking (1986) has shown that columnar ice samples loaded parallel to the elongated crystal axes have compressive strengths 2 to 4 times higher than samples loaded normal to the direction of elongation. Mixed ice samples with large ($> 10\text{-cm}$) fragments of columnar ice are also affected by the orientation of the columnar ice within them. If the columnar fragments in the sample are oriented with the direction of crystal elongation parallel to the load ($\sigma_z = 0^{\circ}$), the sample will fail at a relatively high load and deformation will occur in the granular material surrounding the columnar fragments. The difference between the mean compressive strength of vertically and horizontally cored samples will depend on the number of columnar test specimens in the test series and their crystallographic orientation relative to the load. The results from the tests on the matched ridge ice sample pairs are discussed in more detail in Richter-Menge and Cox (1985).

The Phase I and II unconfined, uniaxial compressive strength data is combined in a mean strength vs strain rate plot in Figure 3. The compressive strength of the horizontal and vertical samples at 10^{-4} /s are noted separately in the figure.

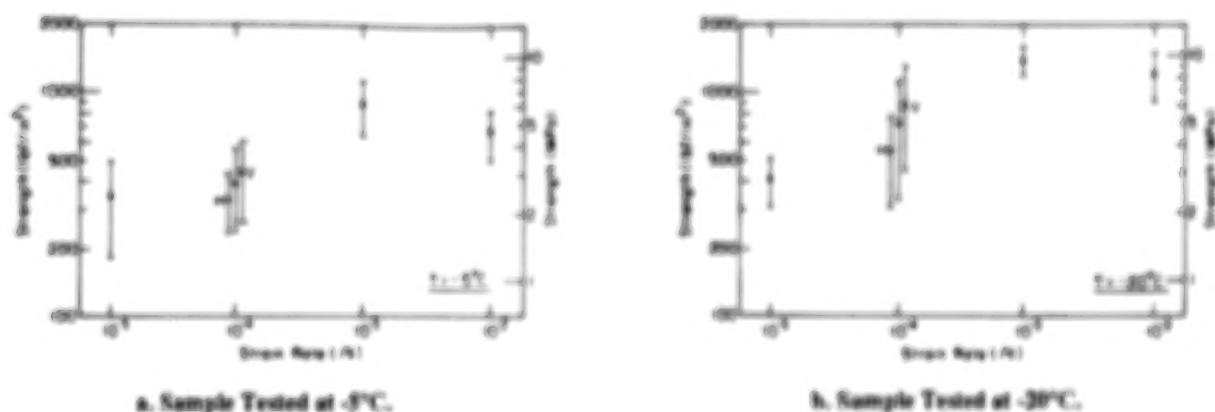


Figure 3 — Unconfined, Constant-Strain-Rate Mean Compressive Strength vs Strain Rate.
H = Horizontally Cored Samples Only, V = Vertically Cored Samples Only. The
Bars Denote One Standard Deviation.

As discussed in the Phase II report on test results (Cox et al. 1985), one would expect a power law relationship between the ice strength and strain rate in the ductile region between 10^{-3} and 10^{-1} (Mellor 1983). This relationship, which plots as a straight line on log-log paper, was not observed in our test results. The porosity variations between the Phase I and II samples appeared to explain this deviation. After analyzing the ice-structure characteristics of the samples tested in each group, however, it became apparent that variations in the overall structural composition of each test group also affect the test results.

The confined or conventional triaxial constant-strain-rate compression tests were done using the triaxial cell developed in Phase I (Mellor et al. 1984). This triaxial cell was designed to ramp the radial confining pressure in constant proportion to the axial stress being applied; $\sigma_1 > \sigma_2 = \sigma_3$, and $\sigma_2/\sigma_1 = \text{constant}$. The Phase II confined compression tests were done at two temperatures (-5 and -20°C), two strain rates (10^{-3} and $10^{-1}/\text{s}$), and two σ_2/σ_1 ratios (0.25 and 0.50). The axial stress and the radial stress are represented by σ_1 and σ_2 , respectively. A total of 55 confined compression tests were completed.

One would anticipate the influence of ice structure in the confined compression tests to be similar to that observed in the unconfined compression tests given the common deformation mechanisms. In general, the investigators observed this to be the case. Columnar samples with a $\sigma:z$ angle near 45° had a low compressive strength. There was an increase in strength as $\sigma:z$ became greater than or less than 45° . The columnar and mixed ice samples from ridge B, which we used in half of these tests, tended to have a high $\sigma:z$ angle.

The confined compressive strength of mixed and granular ice samples shows a strong tendency to decrease with an increase in porosity at all test conditions. Those mixed ice samples with a high percent of columnar ice (80% or more) lie on the outside of the strength vs porosity band. This is a result of the orientation of the columnar fragments within the sample.

Direct tension tests were done on 36 multi-year-ridge ice samples in Phase II of the program. All of these samples failed along a plane normal to the applied load.

All but six of the multi-year-ridge ice samples tested in tension consisted of a mixture of columnar and granular ice. Three of the remaining samples were columnar and three were granular. To gain a more complete understanding of the influence of ice structure on the tensile strength of the multi-year ice, the Phase I multi-year floe ice test results were included in the analysis. The floe ice was predominantly columnar. Based on the combined results, it appears that the tensile strength of multi-year ice shows little dependency on ice type. The columnar ice samples tend to have a higher strength than the mixed and granular ice samples at all test conditions. This is due to the generally lower porosity of these columnar samples rather than differences in the ice type. If the columnar structure of the ice was the reason for the increased tensile strength, one would expect to see a relationship between the orientation of the columns relative to the load ($\sigma:z$) and the strength. Such a relationship has been observed by both Peyton (1966) and Dykins (1970) in tests on first-year sea ice samples. The test data do not indicate this trend.

Results from direct tension tests on freshwater, equiaxed polycrystalline ice (Curry and Schulson 1982) show an inverse relationship between grain size and tensile strength. This relationship was not apparent in the test results. A tendency for the mixed samples ice to fail in the part of the specimen where the grains were coarser was observed. There were exceptions, including mixed ice samples with columnar fragments oriented in the hard fail direction ($\sigma:z = 0^\circ$). These samples failed in the finer-grained ice that surrounded the fragments. Other mixed ice samples failed at abrupt changes in ice structure. One consistent observation was the coincidence of failure planes with large ($> 1\text{ cm}$), isolated voids in the samples.

Conclusion

A total of 14 multi-year pressure ridges have been sampled in the course of this mechanical properties test program. We have structurally analyzed ice test specimens from 13 of these ridges. Table 3 lists the number and percent of columnar samples tested in each of the ridges. The Phase I and II test results suggest that these mixed ice samples behave similarly to the columnar ice samples.

Table 3 — Columnar Ice Samples Tested in Phase I and II. These Samples Include Both Columnar and Mixed Samples With 80% or More Columnar Ice.

Ridge no.	Total samples tested	Total columnar samples	% columnar samples
Phase I			
1	20	13	67
2	24	4	17
3	20	3	15
4	22	6	27
5	20	1	5
6	12	0	0
7	20	6	30
8	24	13	54
9	24	1	4
10	24	8	33
Phase II			
A	46	1	2
B	24	9	37
C	52	20	38
Total	373	91	24

The amount of columnar ice varies from ridge to ridge. As discussed in the Phase I ice structure analysis report (Richter-Menge et al. 1987), these differences are due to the mode of formation of the ridge. Ridges initially formed by the compression of one first-year ice sheet against another contain large blocks of columnar ice. The ice in a ridge formed by shearing, on the other hand, is highly fragmented. Samples taken from ridges should reflect these differences. One would expect to get a higher percentage of columnar samples from a multi-year pressure ridge formed by compression than from one formed in shear.

A frequency histogram of the number of columnar samples in a given σ_z orientation is presented in Figure 4. The frequency histogram of the Phase I columnar samples was originally presented and discussed in Richter-Menge et al. (1987). Based on this observation, it was concluded that in the 10 ridges sampled during Phase I the blocks of columnar, first-year sea ice that were incorporated into the ridge during its formation were lying in a near horizontal position. Phase II unconfined compression tests on matched horizontal and vertical pairs collected during the second field program confirmed the hypothesis (Richter-Menge and Cox 1985).

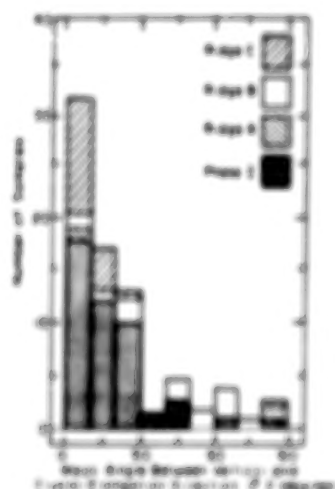


Figure 4 — Frequency Histogram of the Phase I and II Columnar Ridge Ice Samples in a Given σ_z Orientation.

Based on our sampled ridge population, it still appears that the columnar blocks within a ridge tend to be in a near horizontal direction with the elongated crystal axis near vertical. The characteristics of the ridge B columnar ice samples show us, however, that this is not always the case. This observation again points out the importance of the ice structure analysis for the interpretation of multi-year ice data. Each data group is unique with respect to the number of granular, columnar, and mixed ice samples and the orientation of the columnar ice within the samples. These variations in ice structure, combined with differences in porosity, will be reflected in the mean strengths.

The ridge building process itself appears to be extremely dynamic, based on the large percentage (approximately 80%) of mixed ice samples in our combined Phase I and II data set. It also appears that there may be a preference for the columnar ice blocks in a ridge to lie in a near horizontal position. This results in a dependency between mean compressive strength and sample orientation. Vertically cored samples tend to give a higher mean compressive strength than horizontal samples.

At the end of the first phase of this testing program it had become apparent that the ice structure in multi-year ridge samples was extremely variable and that the structure had a profound effect on the mechanical properties of the ice. The Phase II test results confirm this observation.

The ice structure analysis of the Phase II unconfined and confined compression tests shows that the effect of ice structure on the compressive strength of multi-year ridge ice samples is independent of the temperature, strain rates, and confining ratios that we used in our test series.

The tensile strength of the multi-year ridge ice samples does not appear to be significantly influenced by ice structure. Rather, the porosity of the sample is the dominant characteristic with respect to strength.

The most significant conclusion drawn from this study is the importance of characterizing the ice structure of each test specimen. It becomes apparent that the structural analysis is necessary for the proper choice and interpretation of constitutive parameters. Without such an analysis, the development of a constitutive law for multi-year ridge ice based on the data from mechanical property tests on ridge samples will be misleading. An ice structure analysis should become a standard procedure in all multi-year ridge programs.

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Punching Shear Resistance of Lightweight Concrete Offshore Structures for the Arctic

Principal Investigator: Dr. H. S. Lew
Structures Division
National Bureau of Standards
Gaithersburg, MD 20899

Objective: To determine the punching shear resistance of heavily reinforced, high-strength, lightweight concrete slab and shell sections representative of proposed concrete offshore structures for the Arctic.

Potentially great sources of oil and natural gas are contained within the Arctic Ocean region of North America. To exploit these reserves will require the design, construction, and maintenance of permanent offshore structures that can withstand the harsh conditions imposed by the Arctic environment. Further, the structural configurations being proposed are sufficiently different from standard construction that uncertainties exist in predicting the behavior of these structures under the severe environmental loads.

The design of arctic structures requires an understanding of the behavior of the concrete exterior walls under high intensity ice loads. Both global and local effects of the ice loading must be considered. Estimates of the ice contact pressures are typically in the range of 400 to 2200 psi, depending on the area of contact between the ice and the structure. These structures must be designed so that under high intensity ice loads punching shear is not the primary mode of failure; a shear failure is sudden and could lead to the progressive collapse of the structure.

Information on the punching shear behavior of thick, heavily reinforced, lightweight concrete sections of the type being proposed for Arctic structures is limited. Provisions in existing standards pertaining to punching resistance have been derived from tests conducted on thin and lightly reinforced sections. The increased thickness, the large amount of reinforcement, and the possible presence of arch action and prestressing all will influence the punching load capacity.

Two series of tests were carried out to investigate experimentally the punching shear behavior of thick, heavily reinforced, lightweight concrete specimens. The first series consisted of 9 plate and 6 shell specimens at approximately 1/6 scale, and the second series consisted of three 1/4-scale plate specimens. The concrete used in the specimens of both series was made with ASTM Type I portland cement, normal weight sand, lightweight coarse aggregate, silica fume at 10% by weight of the cement, superplasticizer, and an air-entraining agent. The mixture resulted in an average compression strength of about 8000 psi, an air content of about 7 percent, and a unit weight of about 115 pcf. Flexural reinforcement in the specimens was about 1.75 percent of the cross section area for each face and in each of two directions. Shear reinforcement ratio ranged from 0.22 to 0.24 percent of the cross sectional area.

All specimens were loaded at the center of the center span. Layers of rubber contained in a steel cylinder were used to help distribute the load uniformly to the specimens.

Conclusions

The addition of shear reinforcement resulted in significant increases in punching shear strengths even with modest shear reinforcing ratios. The increases in strength produced by the shear reinforcement were greater in the plate specimens than in the shell specimens. Additionally, the increases in strength in the shell specimens were greater in those with the lesser curvature. Also, the presence of curvature in the specimens produced significant increases in punching shear strength. The relative increases in strength decrease with the increasing curvature.

In the plate specimens, the addition of shear reinforcement resulted in a ductile failure. In contrast, failures in all of the shell specimens were sudden. In the shell specimens with shear reinforcement, an upper limit on punching shear strength appeared to have been reached whereby the concrete controlled the strength and a brittle failure mode resulted.

Punching shear provisions in the ACI Code (318-83) are conservative with respect to the test results, particularly for the specimens with shear reinforcement. The test results indicate that different failure conditions occurred in the specimens of this project than are considered by the code provisions or that were observed in other punching shear tests performed on specimens representative of conventional construction. The major reasons for the increased strengths observed in the test specimens are the relatively small span-to-thickness ratios of the specimens, the superior performance of the headed shear reinforcing bars used in the study when compared with conventional shear stirrups, and the presence of arch action due to shell curvature.

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An Investigation of the Nonlinear Behavior of Compliant Risers

Principal Investigator: Prof. N.M. Patrikalakis
Massachusetts Institute of Technology
Department of Ocean Engineering
Cambridge, MA 02139

Objective: To formulate a mathematical model and provide a solution technique for the three-dimensional nonlinear static and dynamic compliant riser problem in the presence of waves, current, platform motion and possible riser-ocean bottom interaction.

Compliant risers are assemblages of pipes with very small overall bending rigidity used to convey oil from the ocean floor or a subsurface buoy to a surface platform. A compliant riser is permitted to acquire large static deformations because of its small bending rigidity and readjusts its configuration in response to large slow motions of the supporting platforms, to which it is rigidly connected, without excessive stressing. Compliant risers have been used successfully in protected waters in buoy loading stations for tankers. Extensions of shallow water concepts have been recently proposed as alternatives to conventional production risers, because they simplify the overall production system.

A mathematical model for the non-linear global static and dynamic behavior of an assemblage of tubes modelled as a non-rotationally uniform slender elastic rod with space varying torque can be found in Patrikalakis and Chrysostomidis (1985) and Patrikalakis (1986). Efficient numerical solutions of the non-linear three-dimensional static problem of a compliant riser in the presence of a steady current can be found in the literature. The numerical solution scheme in the references employs a novel embedding technique which starts by using two-dimensional solutions as initial approximations. The initial approximations of the solution of the corresponding two-dimensional static problems are analytical and are derived using asymptotic techniques. These analytical solutions correctly account for all major external and restoring forces for each case and, therefore, provide excellent initial approximations of the solution of the non-linear static problem. For this reason, fast convergence of the embedding sequence and the associated Newton-Raphson iterations employed in the numerical solution of the non-linear problem is observed in Gurnoy (1985) as opposed to the more usual incremental loading method. Efficient solutions of the linear unforced and undamped dynamic problem of a compliant riser around a non-linear static configuration to determine natural modes and frequencies using a combination of embedding and asymptotic techniques can be found in Patrikalakis and Kriezis (1987a). These publications summarize the results of Phase I of our work.

In Phase II of the research we extended the theory developed initially to allow for three-dimensional non-linear static and dynamic analysis of non-rotationally uniform compliant risers with torsion in the presence of unidirectional monochromatic surface gravity waves traveling at an arbitrary angle, arbitrary monochromatic motions and rotations of the upper and lower ends, of the same frequency as the waves, and arbitrary currents. In this work, the effects of riser-ocean bottom interaction, present in some catenary configurations, and of non-linear drag primarily due to separation and wake formation were taken into account.

The solution is iterative and involves the following steps, Patrikalakis and Kriezis (1987b):

1. Solution of the non-linear static problem in the presence of mean forces and moments due to the currents and waves (possibly involving static riser-ocean bottom interaction).
2. Linearization of the structural part of the non-linear dynamic equations around the static configuration for small dynamic motions and angles.
3. Equivalent linearization of the non-linear riser-ocean bottom interaction forces.
4. Equivalent linearization of the non-linear drag force and moment assuming monochromatic three-dimensional excitation and response.
5. Solution of the resulting non-linear boundary value problem modeling compliant riser dynamics, possibly involving riser-ocean bottom interaction, in the frequency domain.
6. Determination of mean forces and moments due to currents, waves and riser motion.

Once these mean forces and moments are obtained, iterate starting from step 1 until a convergent solution is reached. This process provides the static configuration and the associated static tension and bending moments; the dynamic motion amplitude and phase and the associated dynamic tension and bending moments for a general three-dimensional monochromatic excitation and response; and the total static and dynamic tension and bending moments.

This program allows the analysis of the global non-linear three-dimensional statics and dynamics of single leg multitube compliant risers in the presence of currents and monochromatic waves and motions and rotations applied at both ends.

The results of this method have been compared with other idealizations, such as the cable idealization, and other solution techniques such as non-linear time domain methods addressing the full beam problems. Details on these comparisons can be found in Patrikalakis and Kriezis (1987b). Comparisons with appropriate cable idealizations, revealed that, as long as the dynamic tension is small compared to the static tension, the maximum dynamic tension based on a cable idealization is close to the tension predicted by the Euler beam equations.

The comparisons with time domain independent non-linear codes for flexible risers using finite element methods confirmed the usefulness of the frequency domain method developed allowing rapid and reliable computations of the response even under extreme excitation. An example of such a comparison is shown in Figures 1 and 2. Figure 1 presents the static configuration of a 420 m long steep wave riser located at 320 meters water depth in the presence of strong current. Both the present formulation prediction (continuous line) and the finite element technique prediction (circle symbol) from Mathison (1986) and Hansen (1986) are shown. As can be seen the agreement is very good.

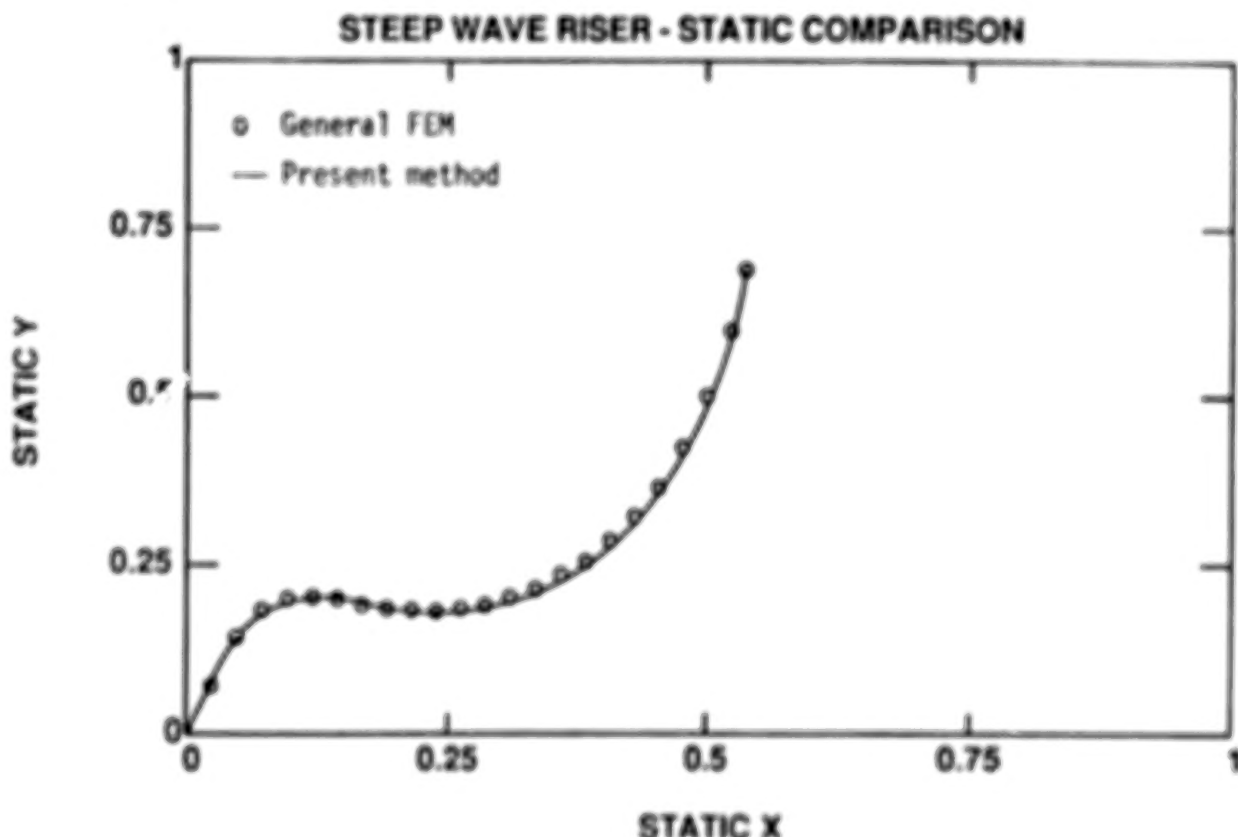


Figure 1 — Static Configuration Comparison for Steep-Wave Riser.

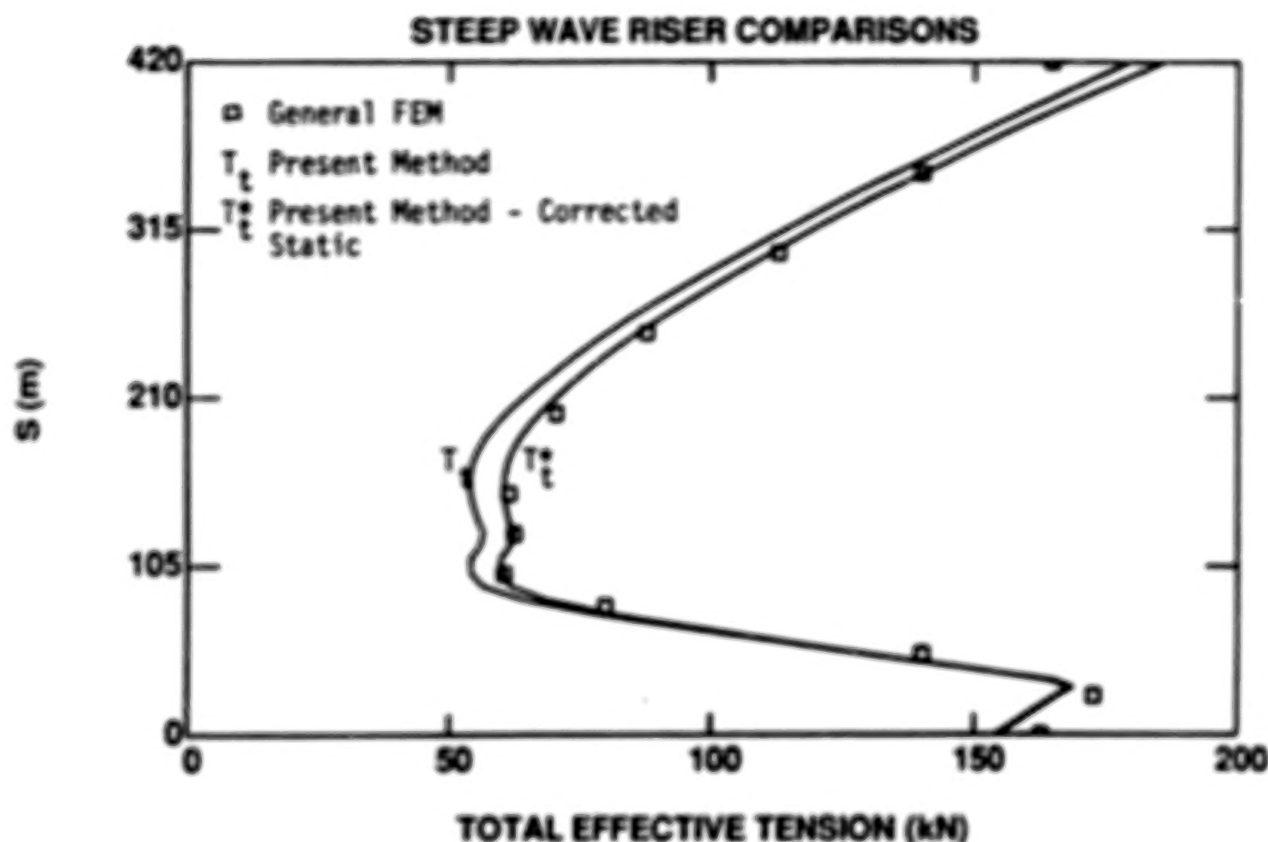


Figure 2 — Comparison for Total Effective Tension from the Two Formulations.

Figure 2 presents a comparison of the maximum total effective tension (static + dynamic) from the two formulations. Two curves from our analysis are shown, corresponding to the corrected static configuration accounting for static effects of waves and dynamic riser motions and to the initial static configuration without wave and riser motion effects. The square symbol corresponds to the finite element method prediction. As can be seen the agreement between the two methodologies is very good. The corrected dynamic result is more accurate than the initial dynamic result from our methodology. The non-linear terms employed in the time domain finite element solution do not appear to significantly affect the response even under extreme excitation conditions as is the case in Figure 2. For this figure, a regular surface wave with amplitude of 15.5 m and period of 16 seconds was used. In addition, the top end of the riser was excited by a heave motion amplitude of 8.99 m with zero phase angle and a surge motion amplitude of 10.37 m with -90 degrees phase angle relative to the wave crest at the top end of the riser. The resulting configuration was two-dimensional in the x-y plane. The comparisons were good for the cases studied but are expected to deteriorate when the dynamic tension exceeds the static tension. In such cases the structural linearization ceases to be valid and a non-linear time domain solution is needed.

Conclusion

The results of this work indicate that the effects of dynamic motion on the static forces and solution are relatively small and therefore may be neglected to a first approximation. The solution method developed based on an adaptive non-uniform grid finite difference technique is successful in efficiently resolving sharp gradients of the solution present either near the supports or at the ends of large buoyancy modules. Dynamic curvature and tension may be significant in comparison to the static quantities and, therefore, dynamic effects should be considered in preliminary design of compliant risers. The static and dynamic curvature is very significant near the top riser end, the touchdown point and requires careful design of strain relief units.

Based on the present research the following recommendations for further work may be made:

1. Develop a frequency domain fatigue program for compliant risers in the presence of direct wave and platform motion excitation. Such a capability is necessary because of the small oscillatory bending radii and large dynamic tensions possible in compliant risers, especially for deeper waters. Reliable laboratory experiments to determine the fatigue characteristics of flexible riser constructions are needed to make the results of fatigue programs useful to the practicing designer.
2. Extend the present methodology for statics and dynamics to multileg configurations. This can be accomplished efficiently because the present method allows incorporation of the effects of compliance at the ends of a single leg system.
3. Investigate the effects of dynamic tension exceeding the static tension and bottom interaction effects (particularly when impact is possible) using a non-linear time domain solution technique.

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Residual Strength of Offshore Structures After Damage

Principal Investigator: Dr. A. Ostapenko
Department of Civil Engineering
Lehigh University
Bethlehem, PA 18015

Objective: To develop a method for analyzing the residual strength of individual members and of offshore platform subframes weakened by damage due to overload and/or by dents and distortions caused by ship impact or falling objects.

In addition to operational and environmental loads, an offshore platform may be subjected to accidental impact by ships or heavy falling objects. Consequently, the platform strength may be significantly impaired by the resulting dents or overall distortions in the bracing members or legs. Such damage to an offshore structure may have serious environmental consequences and may jeopardize the safety of its crew, Taby and Moan (1985), Ellinas and Valsgard (1985). The goal of this research is to provide engineers with tools for assessing the residual strength of damaged offshore structures.

The research project was started at Lehigh University in 1985 and was originally described in Ostapenko (1986). The specific research areas are the indentation behavior of tubular members, that is, the load vs. dentdepth relationship; axial load vs. shortening behavior of dented tubular columns; and strength and load vs. deformation response of offshore frames with dented members. Testing, analytical solution and the development of a practical simplified procedure are involved in each area.

As a part of the study, denting and axial load tests were conducted on two large-diameter (40 and 60 inch dia.) specimens fabricated by cold-rolling and welding which is the typical process used in the construction of offshore structures, Padula and Ostapenko (1987a) and (1987b). Additional test results were taken from literature. However, only tests on small scale manufactured specimens have been available, Taby and Rashid (1980), Taby and Moan (1985), Smith (1983).

The indentation behavior of tubular members was analyzed in the current project by using the finite element program ADINA. The problem is geometrically and materially nonlinear, and it presented considerable challenge in developing a finite element model. Indentation by a transverse load applied through a rigid indenter was modeled by a series of long truss elements each having a unique bilinear or trilinear stress-strain relationship, to accommodate the initial gap between the indenter and the circular tube. The tube was modeled with isoparametric shell elements with as many as 80 degrees of freedom. It was found that the computed load-dentdepth relationship was in much better agreement with tests on stress relieved manufactured tubes than on fabricated ones. An approximate analysis showed that this should have been expected since the finite element method did not consider the residual stresses which exist in the fabricated specimens due to cold-rolling and welding. A simplified approximate method was developed for the load vs. dentdepth relationship by using multi-variable regression analysis of the test data available in literature on manufactured tubes subjected to "knife edge" loading, Taby and Rashid (1980). A typical load-dentdepth relationship is shown in Figure 1 where one curve represents the test data, one the finite element solution and one according to the approximate method. The agreement of these curves gives credence to the accuracy of the simplified method. It should be noted that the area under the curve provides the energy dissipated during indentation and, thus, can be used in determining the amount of damage for a specified collision. Figure 2 depicts the relationship provided by the approximate method between the load variable Q , the dent depth variable W , and the diameter-to-thickness (D/t) variable B .

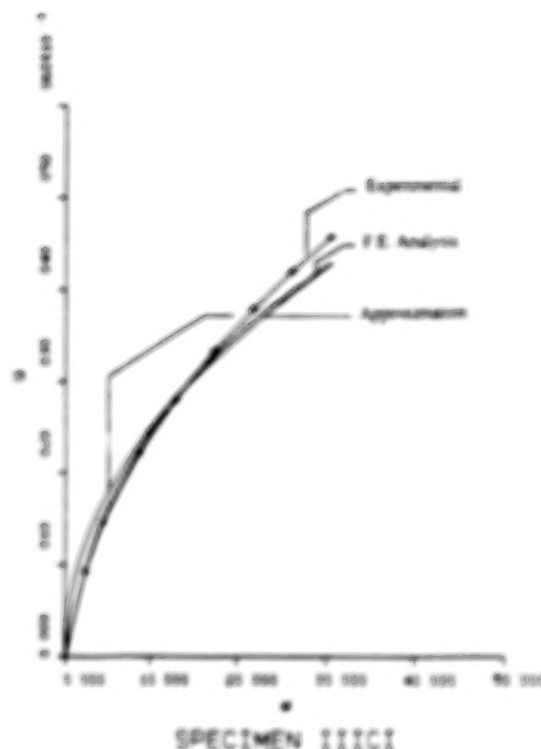


Figure 1 — Load vs. Dentdepth Relationships; from Experiment, F.E. Analysis and Approximate Method.

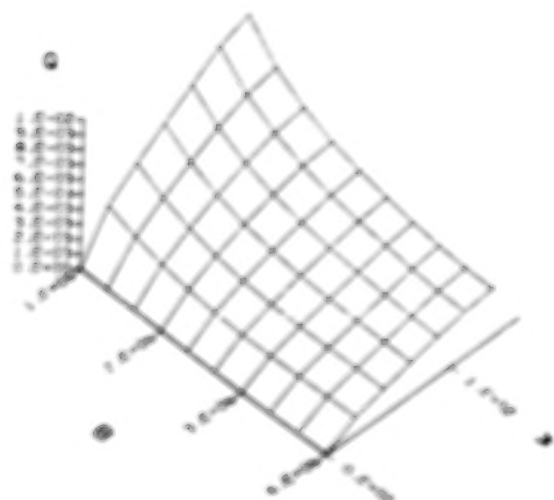


Figure 2 — Load vs. Dentdepth Relationship as Function of the Diameter-to-Thickness Ratio.

Since the present approximate method is limited to $40 < (D/t) < 60$, Padula and Ostapenko (1988), it is planned to extend the method to $(D/t) > 60$ by relying on finite element solutions and on any additional test results which may become available to generate an adequate data base. Besides D/t , dent geometries other than knife edge, and the concurrent axial load and bending moment will be included as variables.

The axial load vs. shortening behavior of dented columns was analyzed by the same finite element program ADINA as was used in the indentation study. So far, only pin-ended columns have been considered.

After considerable experimentation with modeling, load increments and tolerances in order to reduce computer time and increase accuracy, the following discretization model was developed: Shell elements were used for the portion of the column, approximately four diameters in length, containing the dent. This is the area in which deformations of the cross section were expected to take place. The end portions outside the segment with the dent were expected to retain their cross-sectional shape and remain linearly elastic, and they were modeled with beam elements. The pre- and post-ultimate load ranges were considered. A typical comparison of the computed relationship with the test result is shown in Figure 3. The agreement of the ultimate capacities is remarkably good. Although not indicated in this figure, the axial deformations from theory and test at the ultimate load agreed within ten percent.

The variables in this analysis are the slenderness ratio L/r , diameter-to-thickness ratio D/t , dentdepth (and dent geometry), the initial out-of-straightness and material properties. Figure 4 gives a sample of a parametric study of the effect of D/t on the load-shortening behavior while other variables are kept constant.

Finite element analysis as used here is extremely demanding in terms of labor and computational resources (considerable cpu time is required on a mainframe computer), thus, unusable for design applications. Some simpler methods have already been proposed such as the recently developed program DENTA, Taby (1986a) and (1986b). However, this is a self-contained program developed for interactive

use and not for incorporation as a subroutine into a structural analysis program. Furthermore, the simplifying assumptions on which it is based make this method less versatile than desired for a nonlinear analysis of damaged offshore structures.

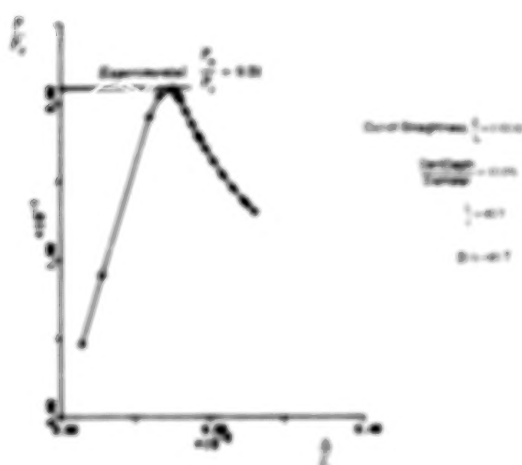


Figure 3 — Axial Load vs. Shortening — Theory and Test.

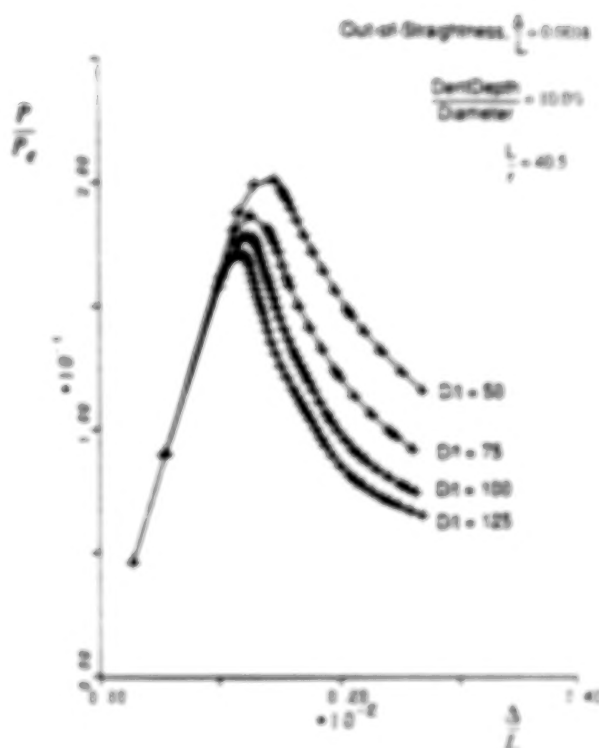


Figure 4 — Axial Load vs. Shortening as Function of D/L .

A more simplified, yet sufficiently accurate, method that could be directly incorporated into the analysis of a frame containing a damaged member is needed. Current effort is spent on the collection of available test results and the generation of additional information by the finite element computer program to create a sufficient data base for performing parametric studies and the development of a simplified method for defining the load-shortening behavior of a dented column once its parameters are specified.

The method is expected to be of the same general form as for the indentation behavior except that there will be many more variables.

Conclusion

The strength and the load vs. deformation response of offshore structures with dented members will provide information on their residual strength and is the ultimate topic of this research. The presently planned approach is to analyze a linearly elastic offshore frame with one or more of the members replaced with dented members. The nonlinear pre- and post-ultimate response of such damaged members will be defined by the formulation developed in the research on dented columns described above.

It is expected that an already available computer program for linearly elastic analysis can be modified to directly incorporate the nonlinear response of a dented member. A one- to three-story sub-frame will be used to determine the redistribution of forces and the residual strength. This will be an incremental iterative procedure demanding considerable time expenditure.

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Development of AIM (Assessment, Inspection, Maintenance) Programs for Offshore Platforms

Principal Investigator: R.G. Bea
PMB Systems Engineering, Inc.
San Francisco, CA 94111

Objective: To develop a practical, general, non-prescriptive, engineering approach to the requalification of existing offshore platforms.

Inspections of offshore platforms have disclosed a wide variety of defects. These defects range from cracks in joints and broken braces to obsolete design criteria. Consequences of such defects were demonstrated in the series of structural failures that occurred in 1985 in the Gulf of Mexico during hurricane Juan (Dyrkeopp, Schonekas, Stewart, 1987).

Currently, there are about 3500 major, fixed, drilling and production platforms installed on U.S. Continental Shelves. About 3000 of these are in the Gulf of Mexico (Figure 1), with the remainder located offshore California and Alaska. Approximately one-third of these structures are over 20 years old.

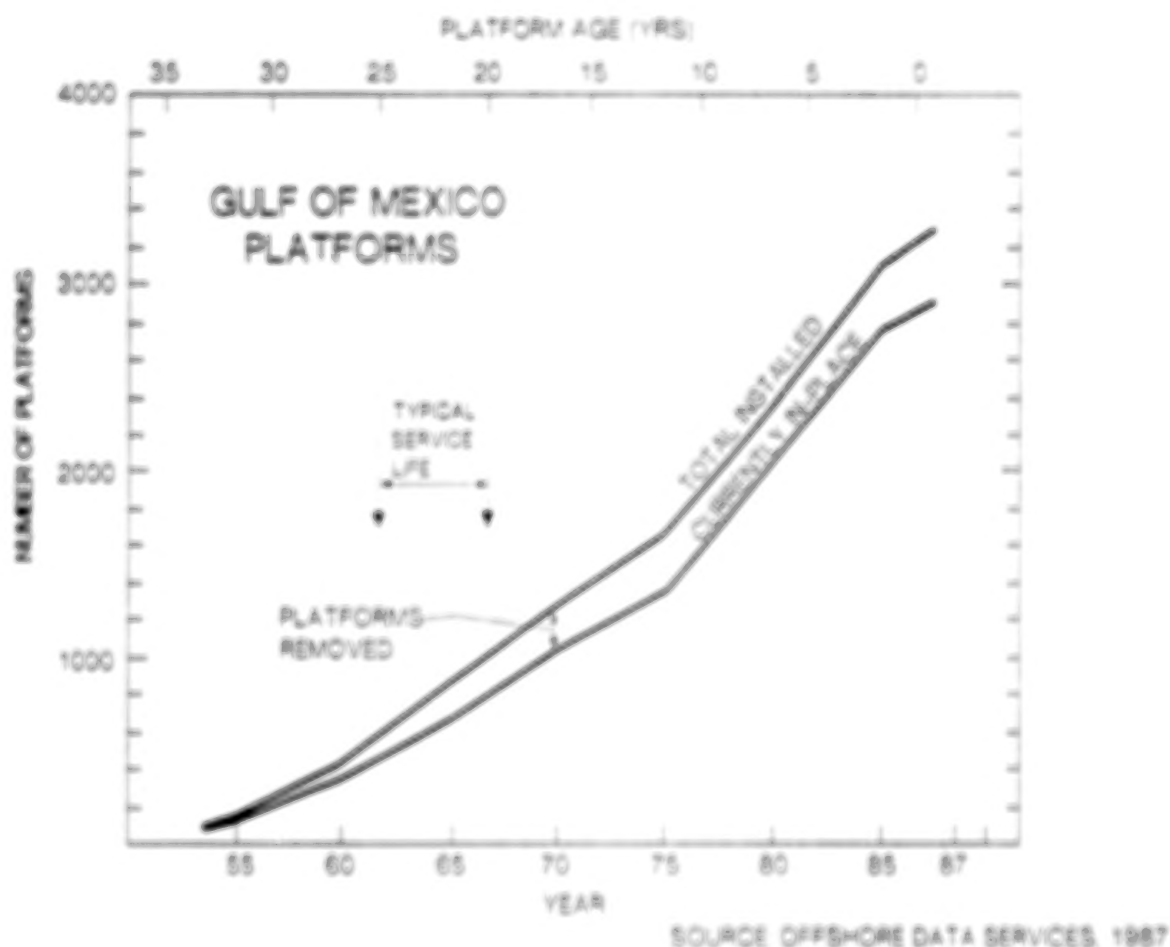


Figure 1 — Gulf of Mexico Platforms.

Platform operators and owners are faced with the need to extend the operating lives and ranges of many of these structures. With depressed and fluctuating oil and gas prices, and increasing maintenance costs, owners, operators, and regulators must find a reasonable way to utilize and requalify existing structures.

Since 1985, the MMS as a member of a joint industry-government sponsored project have been developing a practical procedure for requalifying defective platforms (Bea, Smith, 1987; Bea, Puskar, Smith, Spencer, 1988). The requalification approach has been founded on three principal elements, identified as the AIM triangle (Figure 2).



Figure 2 — AIM Approach.

A - Assessment: those engineering appraisals intended to evaluate present and future platform serviceability, and determine the desirable characteristics of present and future platform performance. This element also includes examining alternative platform maintenance programs with the objective of identifying practical candidates. These programs are focused on developing acceptable platform serviceability characteristics, while preserving essential safety, economic and environmental objectives.

I - Inspection: those engineering and operations programs directed toward detection and documentation of defects in a platform that can lead to significant reductions in serviceability characteristics. This element includes definition of what should be inspected, when, and how, and archiving the results for future AIM cycles.

M - Maintenance: those engineering and operations programs developed and implemented to preserve or enable a platform to develop acceptable serviceability characteristics. This element includes consideration of a wide variety of maintenance programs intended to reduce and mitigate hazards or risks, i.e., load reductions, structure strengthening, reducing operations exposures, and increasing maintenance effectiveness.

The AIM approach (Figure 2) is divided into three primary phases. First is a screening phase that consists of the selection of a candidate platform based on its defect and consequence potentials, performing a condition survey to determine its present condition, then determining if the structure has significant defects that warrant mitigation.

The second phase is a detailed evaluation phase that is entered if it is determined that there are potentially significant defects that need remedial measures. Various alternatives for making the platform meet serviceability requirements are identified and evaluated. The best remedial alternative for the current AIM cycle is selected based on acceptability criteria.

The third phase is an implementation phase that is initiated by designing or engineering the remedial alternative, implementing it, recording the results, and then defining the next AIM cycle.

The first phase of the AIM program is Identification. This consists of the platform operator or owner selecting a platform to enter the AIM process. This platform might be a representative from a fleet of similar structures. The selection should be based on two primary criteria: 1) consequence potential, and 2) defect potential. Consequence potentials include such things as the potential for damage to property, lives, resources, and the environment. The defect potential is an evaluation of the likelihood of deficiencies in design, construction, and operations (including maintenance) of the structure. The initial AIM platform candidates should be those that have both high consequence and defect potentials. Then, as resources are available, lower priority structures are entered into the process.

It is the platform owner's responsibility to take the initiative in the identification, for the owners bear the primary responsibilities for the integrity and serviceability of the structure. It is also the platform owner or operator who is in the best position to see that adequate experience, and operations and engineering backgrounds are integrated into the judgments of consequence and defect potentials. However, the regulatory agencies are responsible to the public and have the authority to require the industry to conduct operations in a safe and pollution-free manner.

The next phase is the Condition Survey. This includes the formation or continuance of a data bank that contains all pertinent information on the design, construction, and operation of the structure (Table 1). Of particular importance are identification and recording of exceptional events or developments during the platform history. These events can provide important clues in determining what, where, how, and when to inspect the platform (Dunn, 1983).

Experience with requalification of structures indicates that the most severe problem is usually the lack of definitive information on the current condition of the structure. The greater the knowledge about a particular structure (or class of structures), then the more realistic is the evaluation and the more effective the mitigation of defects.

Note that condition surveys and future AIM cycles imply the need to develop data banks (files of information) on the structures (Bourgeois, Gerhardt, 1987; Frisbie, 1987). This data bank becomes vital in directing the course and type of inspections.

Inspections of fixed and mobile platforms have been addressed by industry, and guidelines have and are being developed to determine inspection programs (National Research Council, 1979; Buslov, Valdivieso, Holdsworth, 1987; Carr, Clayton, Bury, Dobson, 1986). A practical strategy is to determine what should be inspected by evaluating potential consequences of damage to those elements. The first priorities for inspection are given to those elements of the structure that have high potentials for damage and high consequences of failure.

Table 1 — Platform Data Bank Components.

1. Design - Site data, criteria, guidelines, procedures, drawings, etc., pertaining to the initial engineering phase of the structure.
2. Fabrication - Specifications, materials, equipment, quality assurance procedures and reports, etc., pertaining to the onshore construction phase of the structure.
3. Transportation - Specifications, equipment, quality assurance procedures and reports, etc., pertaining to the load-out and transport of the structure to the offshore installation site.
4. Installation - Specifications, equipment, materials, quality assurance procedures and reports etc., pertaining to the preparation for placement and replacement of the structure at the location.
5. Operations - Information pertaining to platform loading and capacity characteristics and modifications that are developed during the drilling phase and during the production phase of operations of the structure.
6. Maintenance - Specifications, equipment, materials, procedures used to preserve or modify the capacity of or loadings on the platform.

Completing the Condition Survey, the next step is screening. In fact, the next two AIM steps are concerned with screening the platform's need for defect mitigation. Note that defects can range from those associated with the original design (e.g. obsolete criteria), to construction (e.g. bad welds, poor materials, misalignments), to operations (e.g. corrosion protection not maintained), to accidental (e.g. from boat collisions, dropped objects).

The determination of "significant" defects is concerned with the evaluation of the structure's capability to be serviceable (or not fail) during the projected operations period (Figure 3). Frequently, such assessments are very easy; it is obvious that the defects are significant. Other times, the assessments are not easy, and analyses need to be performed to make the evaluations (Lloyd, Clawson, 1983). If there appear to be significant defects, the next step is to determine if mitigation of these defects is necessary.

Mitigation of defects refers to a prioritization of remedying those defects, and identification of practical alternative remedial actions. If no mitigation appears to be warranted, the procedure branches to design of the next AIM cycle.

In the AIM approach, defect mitigation is defined in a very broad context; hence, the maintenance aspect of the AIM triangle. Defect mitigation is much more than "if it's broken, fix it." Defect mitigation alternatives include:

- Reducing platform demands — minimizing loadings and load effects.
- Increasing platform capacities — maximizing or increasing the strength of elements that comprise the structure.
- Reducing operations exposures — decreasing the potentials for injuries to personnel (demaning, lifesaving equipment), damage to the structure (controlling boat operations and trash disposal), losses of the resource (downhole shut in equipment), and injuries to the environment (pollution control measures).

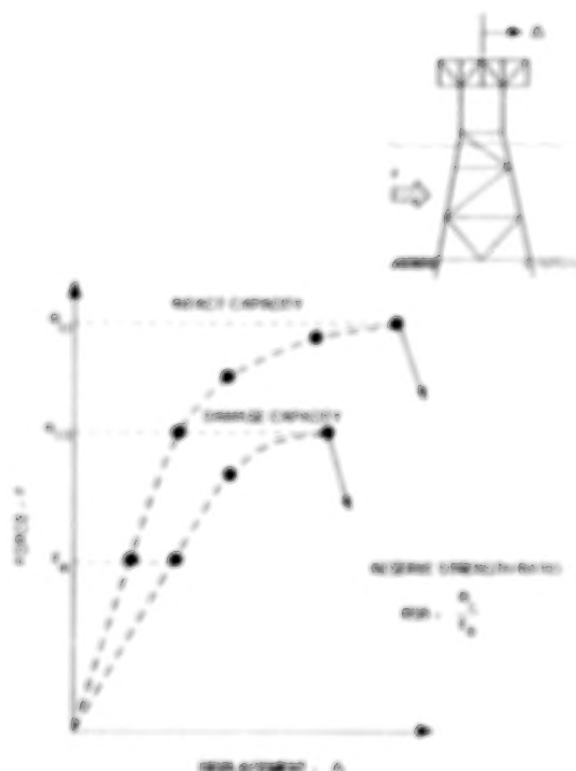


Figure 3 — Platform Capacity Evaluation.

- Increasing maintenance effectiveness — increasing corrosion and scour protection, frequency and extent of inspections, and effectiveness of maintenance engineering and damage reporting systems.

The next step is Evaluation of Alternatives. The process of selecting the most viable AIM alternative can be organized into three steps: (1) structuring the alternatives; (2) determining the consequences of the alternatives; and (3) evaluating the alternatives.

Structuring the alternatives is the identification of the practical AIM strategies for developing an acceptable level of serviceability and safety for the structure and its proposed operations. These strategies are combinations of the hazard mitigation measures previously cited.

Assessment of possible consequences resulting from each of the various AIM alternatives can be performed by using existing data, new data, engineering judgment, or any combination of these. This assessment essentially describes what will or could happen should any of the alternatives be selected, including: a) the potential costs and outcomes associated with a particular AIM alternative, and b) the potential costs and outcomes associated with the maintenance of platform capacity for a particular AIM alternative.

Potential costs include all investments of resources required to implement an alternative, generally evaluated in terms of dollars or equivalent units (Weidler, Karsan, 1983). Due to the uncertainties in many parts of these costs, it is advisable to make evaluations of the most likely cost (best estimate), and cost range (reasonable upper and lower bounds).

Similarly, it may be necessary to introduce ranges in potential outcomes from a particular alternative. These potential outcomes should be focused on the ability of an alternative to maintain the platform capacity at a given level. This is a way to enter the uncertainties associated with the effectiveness of the alternative, such as the uncertainties associated with the effects on capacity of a particular repair plan.

Evaluating the alternatives consists of defining the expected risk and cost ranges for each of the alternatives, ranking these, and selecting the most desirable or acceptable alternative. In terms of economics, this is a process of finding that alternative that produces the lowest total of initial and future

costs. In terms of safety, this is a process of finding an alternative that will produce an acceptable level of platform strength, consistent with potential consequences, and meet the required regulatory criterion (e.g. Figure 4).

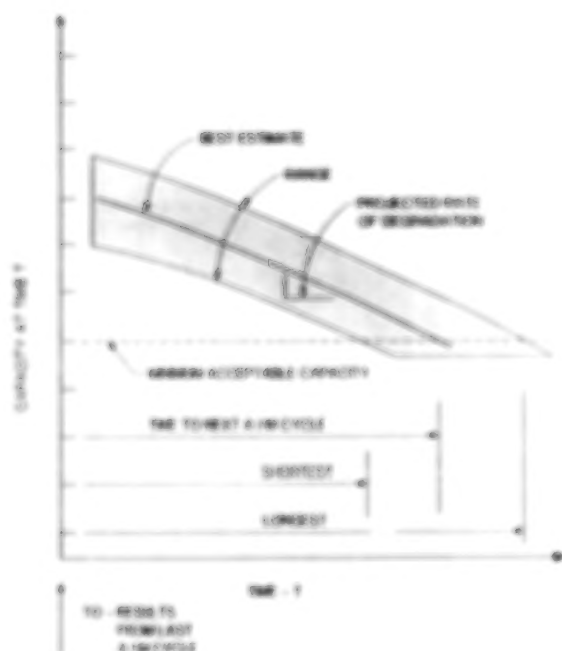


Figure 4 — Capacity-Consequence Evaluation.

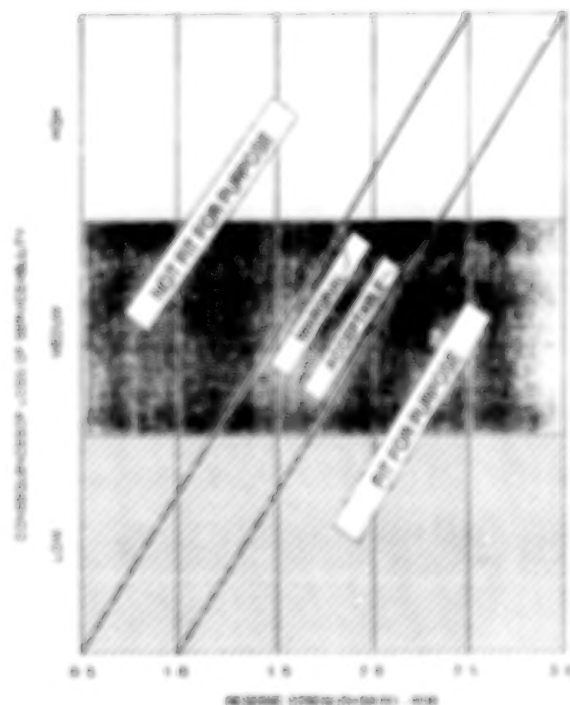


Figure 5 — Timing of AIM Cycles.

Once an AIM alternative is selected, the next step is to engineer that alternative, and implement it in the platform operations. The results of the implementation are incorporated into the platform condition survey and inspection data bank.

The concluding step for a platform is that of designing and implementing the next inspection and maintenance cycle. The length of the cycle (Figure 5) will depend upon the projected performance characteristics of the platform (i.e., how fast the capacity of the structure might be deteriorating), and the need for and benefits of improving knowledge and data on the platform condition and performance (reducing uncertainties).

Conclusion

The AIM approach has been founded on a series of important philosophies that include:

- Practicality for applications in present engineering and operations frameworks, addressing the needs for simplicity, versatility, compatibility, workability, and consistency.
- Keeping structures in service by using preventative and remedial engineering techniques; a positive approach.
- Establishing and maintaining the integrity of a structure at the least possible cost, without compromising professional and safety standards; an approach in which the investment of resources is justified by the scope of benefits achieved.
- Lowering the risks and consequences associated with operations of a structure to the minimum that is practically attainable, recognizing that comprehensive solutions may not be possible due to limitations posed by funding and technology, and that practicality implicates an incremental investment in identifying and remedying structure defects in the order of the hazards they represent; a prioritized, learn-your-way-through approach.

Inspections, definitions of defects, and maintenance of platforms must be given high priority in

platform operations if structures are to retain high degrees of serviceability. Poorly maintained structures cost. It costs scarce resources to maintain structures. However, platform AIM investments can return significant dividends by increasing platform capabilities, lowering the incidence of serious down-time events, and lowering future repair costs.

The problem of platform requalifications is one that should be approached without rigid conformance to "conventional practice". The objective is to maintain a high level of professional and operating excellence by defining creative and practical ways to lessen risks within the unavoidable constraints of currently available knowledge, manpower, money, and time. This is a structure and problem-specific approach. It is not an engineering code or rigid guideline approach.

AIM I was sponsored by the Minerals Management Service and the project was guided by an advisory panel.

AIM II was sponsored by eighteen organizations including the American Bureau of Shipping, Amoco, Aroc, Chevron, Cities, U.S. Coast Guard, Conoco, Elf, Marathon, Exxon, McDermott, Minerals Management Service, Mobil, Phillips, Shell, Statoil, Texaco, and Unocal.

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Development of a Method to Evaluate the Tension Capacity of Drilled and Grouted Piles

Principal Investigators: Dr. Jean-Louis Briaud
Mr. Richard M. Dupin
Texas A&M University
College Station, TX

Objective: To examine the feasibility of adapting cement logging technology to the inspection of the grouted annulus in large diameter drilled and grouted piles, and hence identify defected grouted zones that contribute to reductions in pile capacity.

Drilled and grouted piles have become an alternative design concept to driven piles in the offshore environment. Due to the lag in pile hammer technology for deep water applications, drilled and grouted piles have been considered a viable replacement as anchor piles for the compliant Tension Leg Platform (Earth Technology Corp., 1986). Furthermore, capacity problems have been associated with driven piles in calcareous sands for nearly twenty years. Drilled and grouted piles in calcareous sands have exhibited capacities as great or greater than driven piles in silica sands (Murfl, 1987).

The installation for drilled and grouted piles involves the use of drilling technology and equipment. Installation essentially involves drilling an over-size hole, lowering a steel casing, and then filling the annular void between the steel casing and the surrounding soil with grout. However, this installation method and the performance of drilled and grouted piles has not received much research attention (Earth Technology Corp., 1986).

Unlike in the case of the driven piles, where one can rely on the driving history during installation for capacity interpretation, the drilled and grouted pile has no accepted method for capacity evaluation during or after installation — short of an actual load test. The inability to adequately and economically determine the installed capacity of the drilled and grouted pile remains a stumbling block for its acceptance. A verification method is needed to assure that the grouted annulus is free of defects such as mud channels or other grout voids which would reduce the actual pile capacity compared to the designed capacity.

Cement logging has been considered as a possible method by which the quality of installation for drilled and grouted piles can be verified. Cement logging is the downhole inspection of the grouted annulus between the soil and a well casing, over the casing's length. Typically, cement logging is performed by wireline service companies which have developed tools to operate in oil well casings.

Various cement logging tools have been developed to log the annulus of cemented or grouted in-place well casings. Several downhole tools have the proven ability to locate anomalies along the steel/grout/soil interface. The anomalies can be construed as defective grouted zones created by mud channeling or large voids which allow for unwanted fluid intrusion into a well. Typically, the tools are used to determine the top of the grout after primary cementation; determine the quality of the steel/grout/soil bond, i.e., how good is the bond between the grout and the steel and between the grout and soil; and to determine the quantitative coverage of the steel/grout bond, i.e., identifies the defective grouted zones with respect to depth (Earth Technology Corp., 1987).

Three types of logging tools may have potential for inspecting the grouted annulus for large diameter piles: refraction, reflection, and nuclear.

Refraction tools are used to evaluate the compressive strength of the grouted annulus layer with depth. Low compressive strengths would indicate that the circumference of the pipe is not totally encased by grout. The principle behind sonic logging is to measure the amplitude or attenuation of sonic energy traveling axially (downhole) along the casing (see Figure 1a). Attenuation of the wave energy occurs as a loss of this energy to the surrounding medium on either side of the casing: mud, water, cement, etc. Since the particle movement at the surfaces of the casing is predominantly parallel to the casing axis, more energy is lost through shear coupling to a solid medium (cement), than to a liquid (mud). The amplitude of the first casing arrival at the receiver is thus indicative of how much cement

surrounds the casing; a high amplitude indicates a free pipe while a low amplitude indicates a cemented pipe (see Figure 1b) (Froelich, Pinman, and Seeman, 1981).

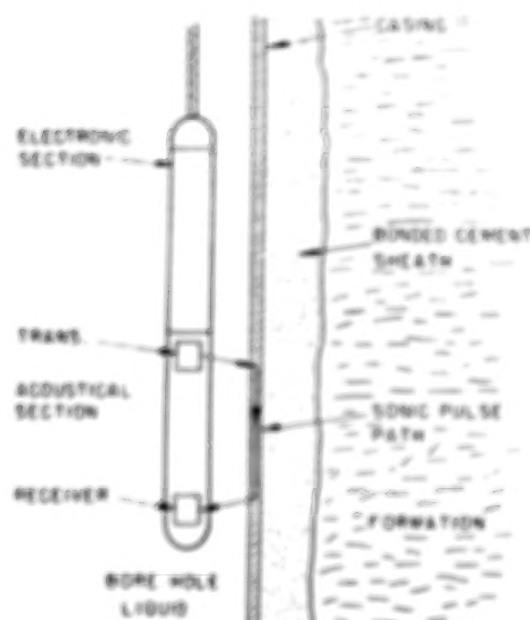


Figure 1a — Schematic of Cement Bond Logging Tool (after Brown, Grijalva, and Raymer, 1970).

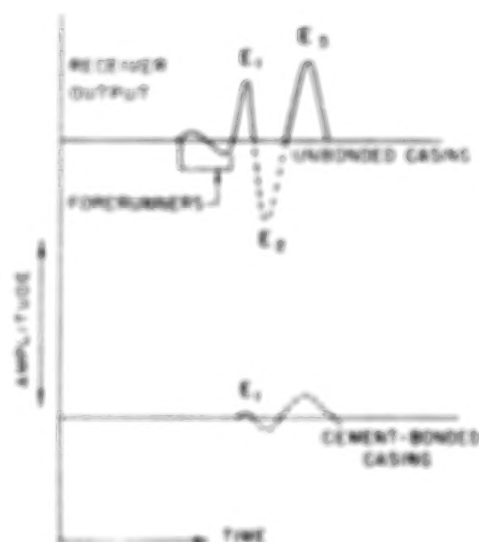


Figure 1b — Schematic of Output Signals for Unbonded and Bonded Casing (after Brown et al., 1970).

Figure 2a represents a cement bond log for a section of free pipe, while Figure 2b represents a cement bond log of a well cemented section of pipe. Notice the high amplitudes for the free pipe and the low amplitudes for the well cemented pipe. Since the sonic energy is transmitted and received radially in all directions inside the pipe, this logging method indicates the grout encasement of the steel as a circumferential average.

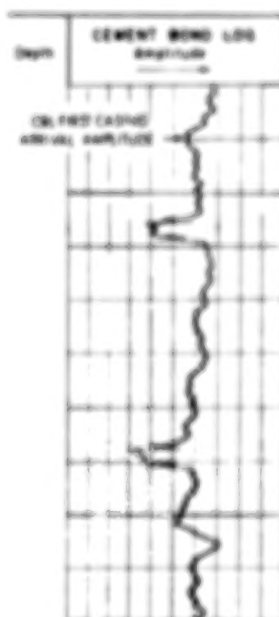


Figure 2a — Cement Bond Log of Free Pipe (after Brown et al., 1970).

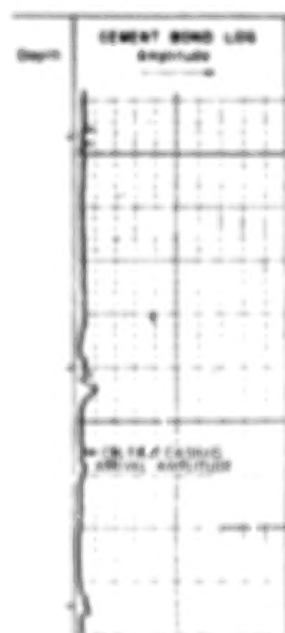


Figure 2b — Cement Bond Log of Well Bonded Interval (after Brown et al., 1970).

Reflection tools differ from refraction tools in that instead of measuring the loss of energy to the surrounding cement, it is based on acoustic impedance of the surrounding cement. By using ultrasonic energy, the casing is made to vibrate. The presence of cement behind the casing is detected if it creates a rapid damping of this vibration. Slow damping of vibration indicates a lack of cement (Froelich et al., 1981). Reflective tools emit and receive energy in a radial pattern with respect to the casing axis and provide an interpretation of the grout integrity by using transmitter-receivers which inspect a 45 degree azimuth. The azimuthal inspection of the casing allows for a more precise determination as to a defects circumferential location.

Nuclear grout tools record the number of "deflected" gamma rays with respect to time. A common use for nuclear or gamma ray logging is the monitoring of the density behind a steel casing. Nuclear grout tools are used to locate the top of a grouted layer. Less dense zones would have a high count per second and vice versa. Figure 3 depicts a gamma ray log for a grouted pipe section. In the figure, the high count per second reading indicates a less dense zone immediately behind the steel casing.

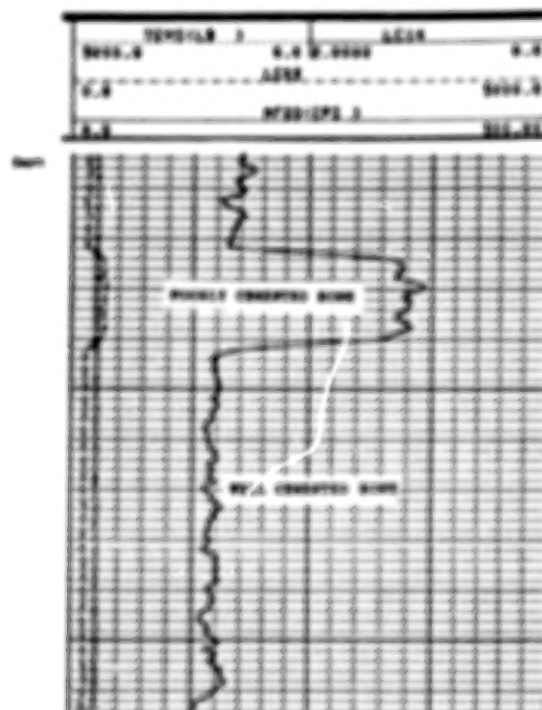


Figure 3 — Nuclear Grout Density Log Locating Free Pipe Section Between Well Cemented Zones (Courtesy of Schlumberger).

By applying cement logging technology to drilled and grouted piles, identification of defective grouted zones which contribute to capacity reduction may be possible, and therefore the application of this technology as a capacity verification method needs to be evaluated.

Because of the larger physical characteristics of piles compared to well casings, modification of cement logging technology is required. The larger pile diameters and thicker walls present an obstacle for reliable performance by standard logging tools. To adequately determine the reliability of cement logging technology for drilled and grouted piles, a "benchmark" test to compare tool interpretations to a known condition is required.

Located at the Texas A&M Research Annex is a 20 in. diameter, 3/4 in. wall, 112 ft. long steel pile, used as an insert to form a composite drilled and grouted pile. The steel pile has been grouted in place with various defects incorporated into the grouted annulus. By logging this benchmark pile, comparisons between the interpreted log and an expected log can be made. This would illustrate a need for further tool modification, if necessary, or verify the accuracy of the tool performance. Figure 4 shows the steel insert about to be inserted into the drilled hole.



Figure 4 — Insert Pile Being Lifted Prior to Placement Into Borehole.



Figure 5 — Schlumberger Operators Positioning Sonic Logging Tool in 20 in. Diameter Insert Pile.

The defective regions have various sizes in order to check the limits of the logging tools. These voided areas have been constructed such that a void can be interpreted as an air space, water space, or mud space by allowing the voided cavity to be filled or flushed with water or mud solutions, or pumped dry. Can different types of nongrout substances be identified as other than regions of low compressive strengths? The identification of the poorly grouted zone contaminate may reflect the type of void and the best way to correct the zone.

The grouted annulus also changes with depth to monitor the effect of varying annulus thickness on tool performance.

By accurately logging the grouted annulus, defective regions can be identified and repaired using high pressure grouting methods as shown in Figure 5. Furthermore, after repairs, relogging can be performed to interpret the success of the remedial grouting operation.

Once the annulus for a drilled and grouted pile can be accurately logged, a prediction of the actual field capacity can be determined. By knowing the borehole diameter, obtained by using downhole calipers, and the quality of the cemented annulus with depth, the field capacity with respect to surface friction can be calculated.

In addition to the cement logging research, load tests will be conducted on two 8 in. diameter, 40 ft long drilled and grouted piles which have 5 in. diameter, 3/8 in. wall steel inserts. One pile was constructed with a fully grouted annulus and the other with an annulus that has an approximate 20 percent decrease in grout to soil bond (see Figure 6). The piles will be tested in static tension and also cycled about a mean tensile load.

The defective pile will be load tested and compared to the load test results of the fully grouted pile. After the first series of loadings on the defective pile, and after allowing time for soil reconsolidation, the defective region will be regouted and another series of load tests will be performed.

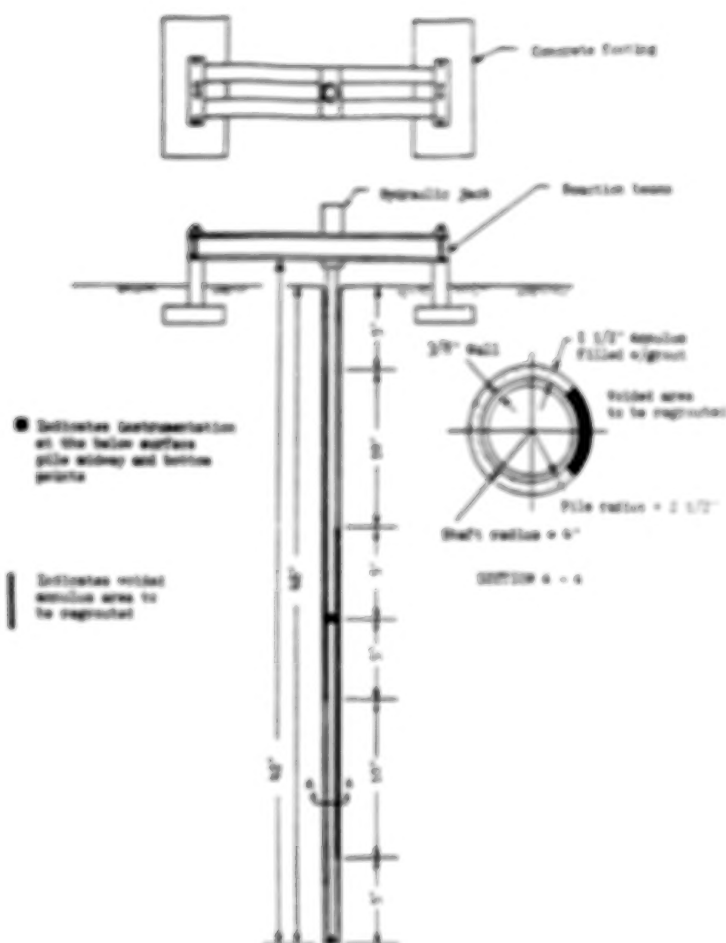


Figure 6 — Load Test Pile, 8 in. Diameter, 40 ft. Long

As a deep water anchor for a tension leg platform, the soil-pile system is subjected to a unique mode of constantly changing tension loads — usually cycled about a bias tension load (Mueller, Audibert, and Bamford, 1987). Because of the low tensile strength of grout, the composite steel/grout/soil system needs to be studied from a fatigue standpoint.

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Hydrodynamic Effects on Design of Offshore Platforms (HEDOP)

Principal Investigators: R.G. Bea
R.W. Litton
S.F. Pawsey
PMB Systems Engineering, Inc.
San Francisco, CA 94111

Objective: To develop and verify engineering analysis procedures to determine hydrodynamic loading effects in offshore platforms.

The traditional extreme wave static design strength methodology has been applied successfully for a number of years. A similar statement can be made regarding the nominal wave fatigue design methodology. Several generations of successful offshore platforms have been the result of this experience based approach.

Recent offshore platform loading and response measurement and analysis programs (Rodenbusch, 1986; Steele, Finn, Lambrakos, 1988; Bea, Pawsey, Litton, 1988) indicate that two aspects of this background need to be carefully evaluated. The response of platforms having significant dynamic forces (Figure 1) is controlled by factors that do not necessarily fall within historic static design methodology. The performance of both shallow and deepwater platforms in recent extreme storms indicates that there may be sources of generally unrecognized conservatism in many widely used formulations of static wave forces.

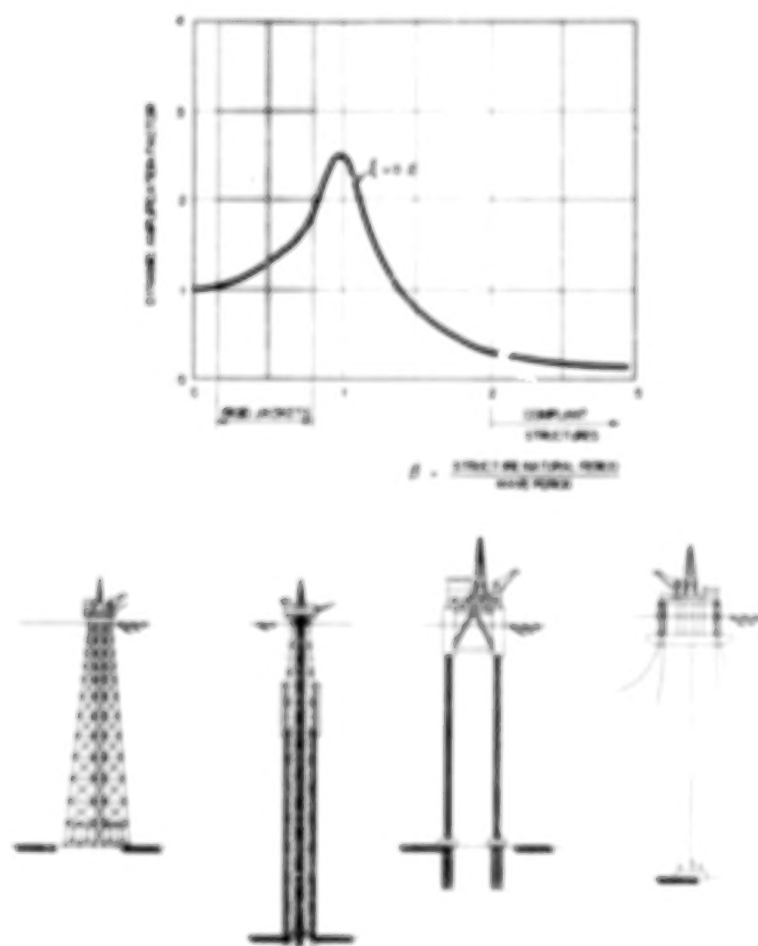


Figure 1.

The engineering aspects of these evaluations can be organized into five principal technical areas of concern (Figure 2):

1. Environmental Conditions – Specification of the combinations of waves and currents, their characteristics, and their magnitudes.
2. Kinematics – Analysis of wave and current induced velocities and accelerations distributed throughout a platform during the events of concern, and during the exposure period anticipated for the structure.
3. Forces – Characterization of the forces imposed on a structure by the water motions, generally cast in the framework of an extended Morison equation (drag, inertia, lift, and diffraction forces).
4. Structure – The platform's geometric characteristics, stiffness, mass, damping and the static (Ws) and dynamic (Wd) loading effects distributed throughout the platform.
5. Design Loads – Combination of static and dynamic loading effects used to proportion the members of a platform, including specification of appropriate loading (γ_L) and resistance (γ_R) factors.

Phase I of HEDOP focused on time-domain analyses of extreme conditions acting on compliant

HEDOP MAJOR COMPONENTS

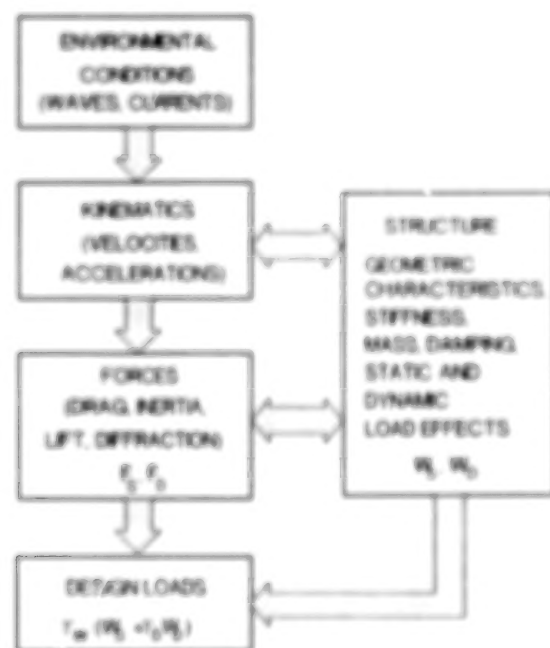
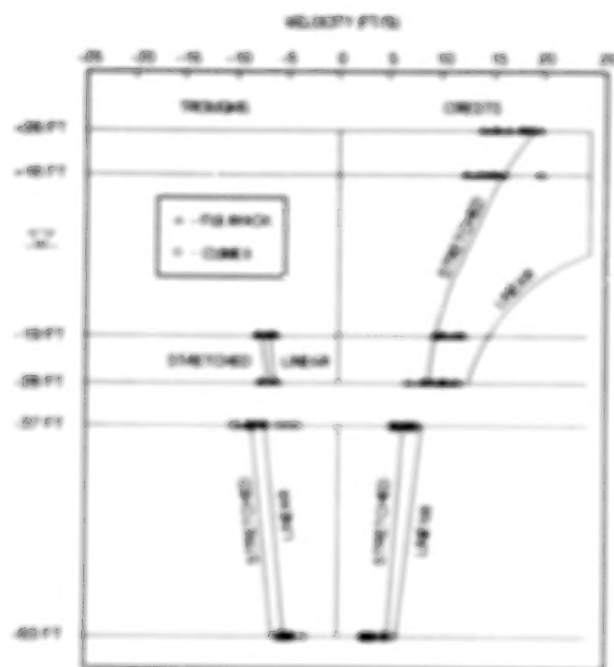


Figure 2.

towers. The project addressed three key issues: a) calculation of water kinematics given a specification of two-dimensional irregular seas and a compliant tower; b) computation of hydrodynamic forces; and c) analytical modeling of the platform to determine dynamic loading and force effects.

The project involved five principal efforts: Hydrodynamic Loadings State of the Art Review (PMB(a), 1987); Structural Dynamics State of the Art Review (PMB(b), 1987); Modeling Procedures Verification Studies (PMB(c,d), 1987); 2000 Foot Water Depth Compliant Tower Parameter Study (PMB(e), 1987); and a Modeling Procedures Documentation (PMB(f,g,h), 1987).



MEASURED VS PREDICTED WAVE KINEMATICS

(AFTER STEELE, FINN, LAMBRAKOS, 1988)

Figure 3.

Three kinematics models were evaluated (Vertical, Wheeler, Gudmestad). In addition, two hydrodynamic force models were considered (conventional coupled Morison, and uncoupled Morison). These models were tested with available kinematics measurements (Figure 3) (Steele, Finn, Lambrakos, 1988), and with available measurements from the Lena Guyed Tower (Figure 4) (Steele, 1986). They were also tested with data provided by Shell from the Cognac platform (Figure 5) (Forristall, Ward, 1987). In all but one test, the HEDOP-I hydrodynamics-structural dynamics modeling procedures gave conservative predictions of the measured responses (Figure 6).

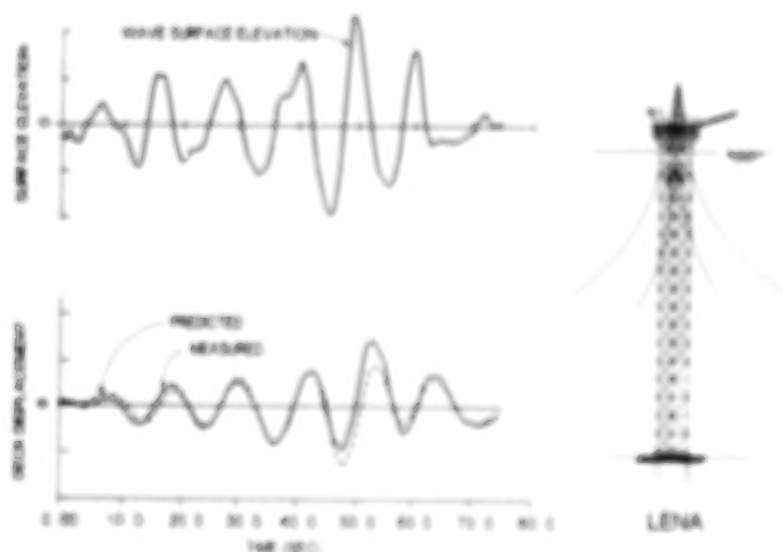


Figure 4.

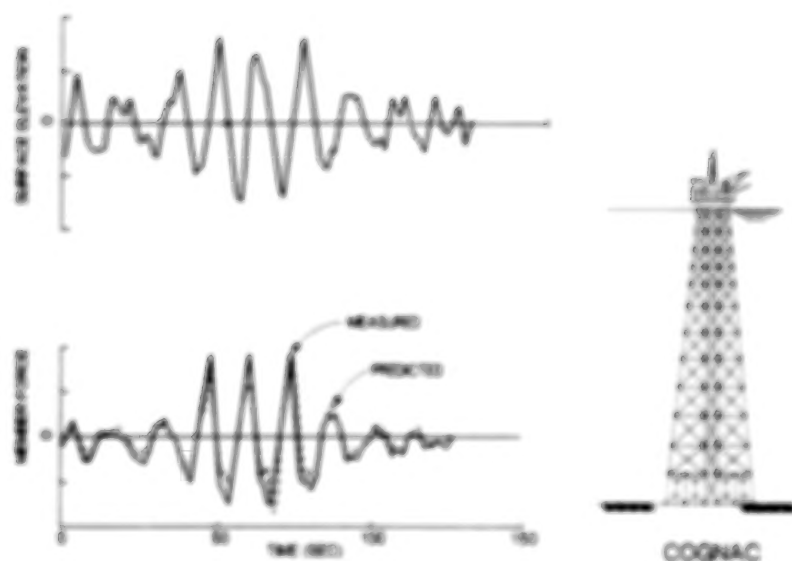


Figure 5.

The responses of a 2000-foot water depth Compliant Tower Jacket (CTJ) were studied parametrically (Figure 7) to determine the most influential factors in the modeling procedures. Kinematics models, shielding models, and current-wake interaction models were found to be the most important factors in determining the global responses of the CTJ. Most of these factors reflected their most dramatic influences in the low-frequency drift responses and static forces of the CTJ.

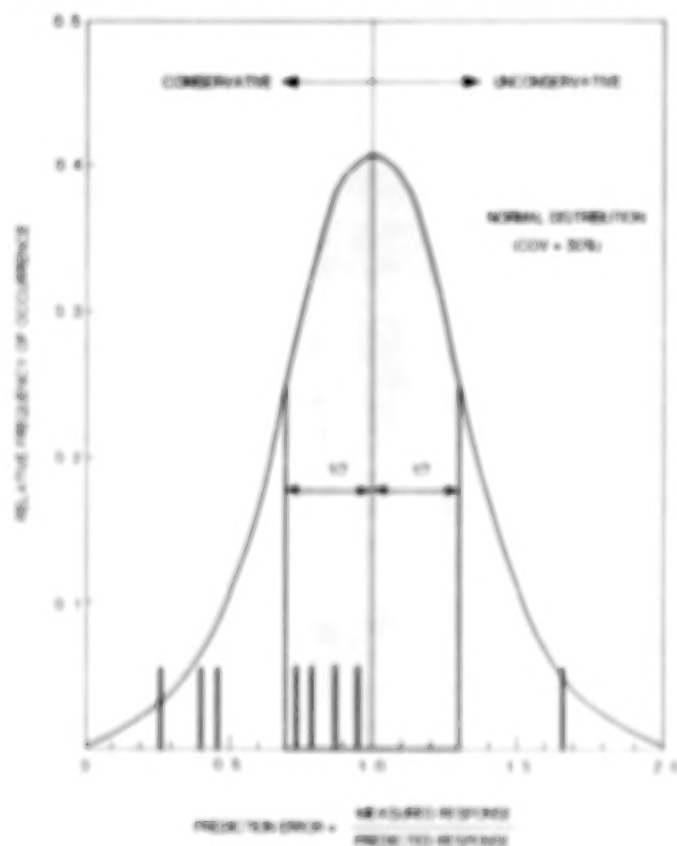


Figure 6.

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Development of RAPRENO_x for Diesel Emission Control

Principal Investigator: Dr. Robert A. Perry
Technor, Inc.
2374 Research Drive
Livermore, CA 94550

Objective: To develop RAPRENO_x, a NO_x reduction technology, for marine and stationary diesel applications.

Marine diesel applications have recently come under severe restrictions in the southern California coastal region. This may impact our nation's ability to drill for oil from offshore platforms. While certain NO_x control strategies exist, their potential application to offshore prime movers is questionable, or at best, expensive. Diesel generators are a potential source of electricity in remote locations, such as offshore oil platforms. The use of a safe, cost-effective way to provide NO_x reduction in diesel applications would make offshore oil exploration less costly while helping to keep the environment clean.

The major goal of this project is to develop the RAPRENO_x process for the removal of nitrogen oxides in diesel exhaust. The patented RAPRENO_x process (Perry, 1987) works by adding gaseous isocyanic acid to an exhaust gas stream. Isocyanic acid is formed from the thermal decomposition of cyanuric acid. Reactions of NO and HNCO generate N₂, CO₂, and water.

While the process has been demonstrated on a laboratory scale diesel engine to remove greater than 95% of the NO_x produced (Perry and Siebers, 1986), further work is needed to develop the technology for large heavy-duty diesel applications. The project will provide the basic groundwork necessary to assess the potential engineering problems associated with diesel applications. The ultimate goal of this program is to develop a commercially viable control technology for heavy-duty diesel applications.

Our approach to the development of a commercial device for heavy-duty diesel applications involves the testing of the process in a multifuel test facility (250,000 BTU/Hr) that is presently under construction. In this facility we will explore the effects on the process of oxygen, nitric oxide, and carbon monoxide concentrations. The gaseous products will be quantitatively measured and the utilization rate will be determined for cyanuric acid as a function of temperature. From this data set, a better understanding of the problems associated with large heavy-duty diesel engines will be possible.

A second part of our research program involves the modeling of the test results using a computer code developed at Sandia National Laboratories. Chemkin, a computer code that has been used to model combustion and NO_x reduction technologies will be used too, and insures a fundamental base for extending the results to large diesels.

The flow diagram of the test facility is illustrated in Figure 1, and the details of the combustor are shown in Figure 2.

The combustor consists of three main sections: 1) the combustion and cooling section, 2) injection section, and 3) test section. Natural gas, or diesel doped with nitrogen containing compounds, is burned in the combustor. The combustor section is nominally 7 inches in diameter and 30 inches long. Gas temperatures leaving the combustor section and entering the injection section are controlled by a series of adjustable water cooled probes. The insertion depth is varied to control the heat removal by each of the probes.

Isocyanic acid is injected into the two diametrically opposed 3/8-inch diameter injectors. The injector section is a venturi section having a 3-inch diameter throat with the exit increasing to match the 8-inch diameter test section. A thermocouple port is located 1 inch above the plane of the injectors.

The test section is 8 inches in diameter and 95 inches long (exit of the injection section to the exit of the combustor). Sampling ports are located along the walls. Additional ports are located across from the sampling ports, as shown in Figure 2, and these latter ports are used for thermocouple access. The test section has two independent electrically heated regions to help maintain isothermal conditions.

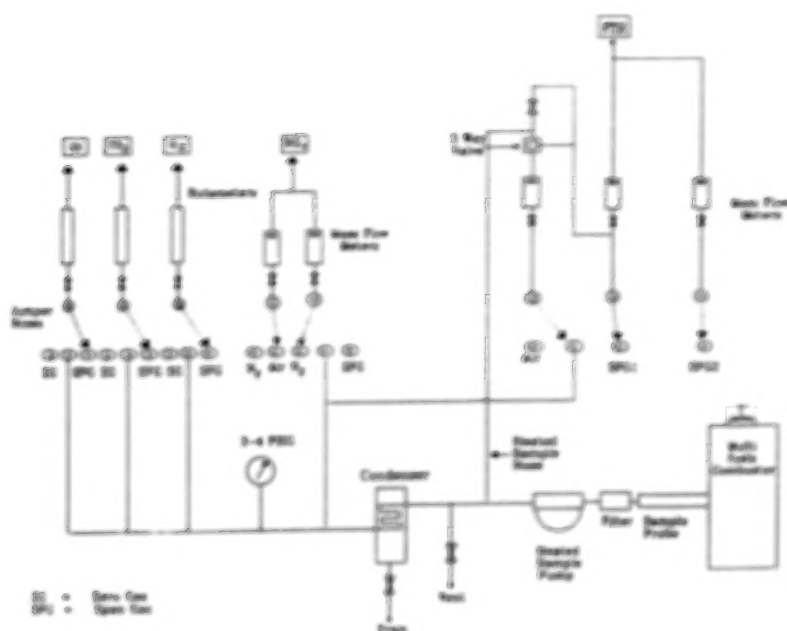


Figure 1 — Gas Analysis System.

Multifuel Flow Reactor

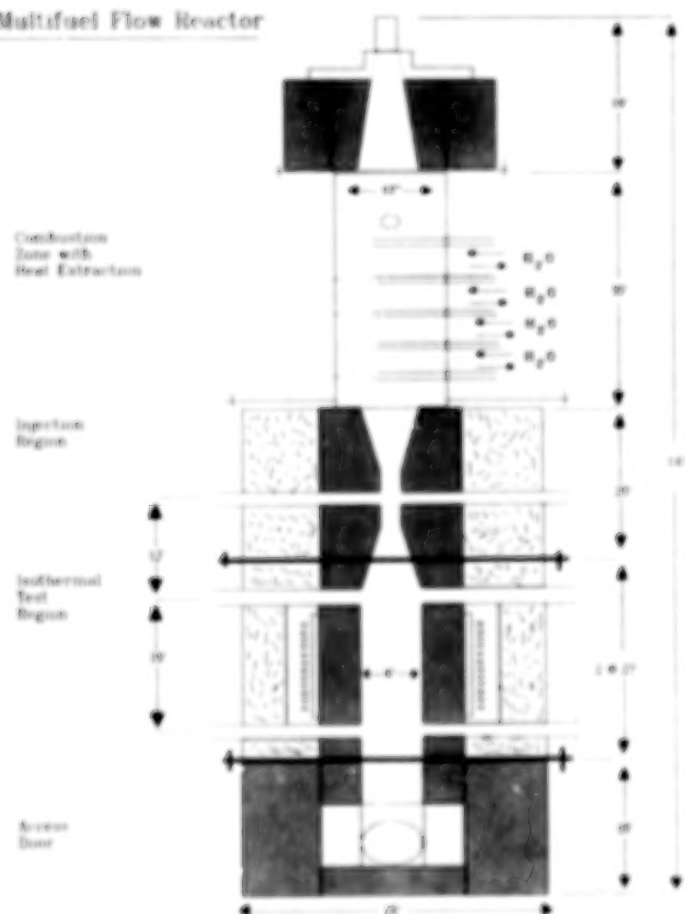


Figure 2 — Multifuel Flow Reactor.

The combustor is fabricated from a castable insulating refractory. The walls are nominally 5 inches thick along the test section. The castable refractory material is wrapped with 4.5 inches of Kaowool ceramic fiber insulation and the complete unit housed in a steel casing.

Gas flows to the unit are metered with rotameters. All temperatures are measured with ceramic shielded Pt-Pt 13 percent Rd thermocouples. A calibration is established between these thermocouples and a suction pyrometer and the true gas temperature obtained during routine testing using the shielded thermocouples and the correction factor obtained from the suction pyrometer. The suction pyrometer temperature, considered more accurate, is approximately 60°C higher than the shielded thermocouples.

Residence times in the unit are changed by varying the sampling location at a fixed throughput through the combustor or by varying the combustor throughput.

The typical ranges of combustor operating parameters are summarized in Table 1. The baseline operating point is shown in parentheses.

Table 1 — Combustor Operating Parameters.

Firing Rates:	70 - 350 kBtu/hr (150,000 Btu/hr)
Combustor Flow Rates:	15 - 70 scfm (22 scfm)
Test Section Velocity:	5 - 33 ft/sec (8 ft/sec)
Test Section Temps:	400 - 1400°C (1100°C)
Residence Times:	0.05 - 1.8 seconds (1.0)
Test Sec. Reynolds No.	1,000 - 10,000 (2,200)

Gaseous and solid samples are obtained from the combustor using a water cooled gas quench probe. A thimble separates the solids and the gas sample is transported to the gas analyzers through a heated teflon sample line.

The flow reactor is instrumented with advanced state of the art instrumentation, including a Fourier Transform Infrared Spectrometer that has been equipped with a 6 meter multipass gas cell having high sensitivity for such gas species as HNCO, N₂O, NH₃, HCN, CO, NO₂, and NO. This system allows for the simultaneous detection of a wide variety of infrared active species having sensitivity better than 1ppm.

Summary

This program sponsored by Technology Assessment and Research Program will provide the data base for the design and operation of a NO_x reduction prototype for large marine diesel applications. We will explore the effects of temperature, oxygen concentration, residence time, surface initiation, combustion species and cyanuric acid usage on NO_x reduction. In addition, we will develop a chemical kinetic model to better predict the most effective way of implementing RAPRENO_x for marine and stationary diesel applications.

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Ice Impact With A Cable Moored Platform

Principal Investigators: Wilfrid A. Nixon
Robert Ettema
Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242-1585

Objective: To determine the forces and displacements undergone by a cable-moored platform impacted by both sheet and rubble ice, by means of model ice tank testing.

Drilling for oil in relatively deep (> 60 ft), ice-covered or ice-infested water poses a number of problems, not the least of which is the provision of a stable platform from which drilling activities can be conducted. One solution to these problems is to use a cable-moored platform (see Figure 1), such as the "Kulluk" platform which has operated for a number of seasons in the Beaufort Sea.

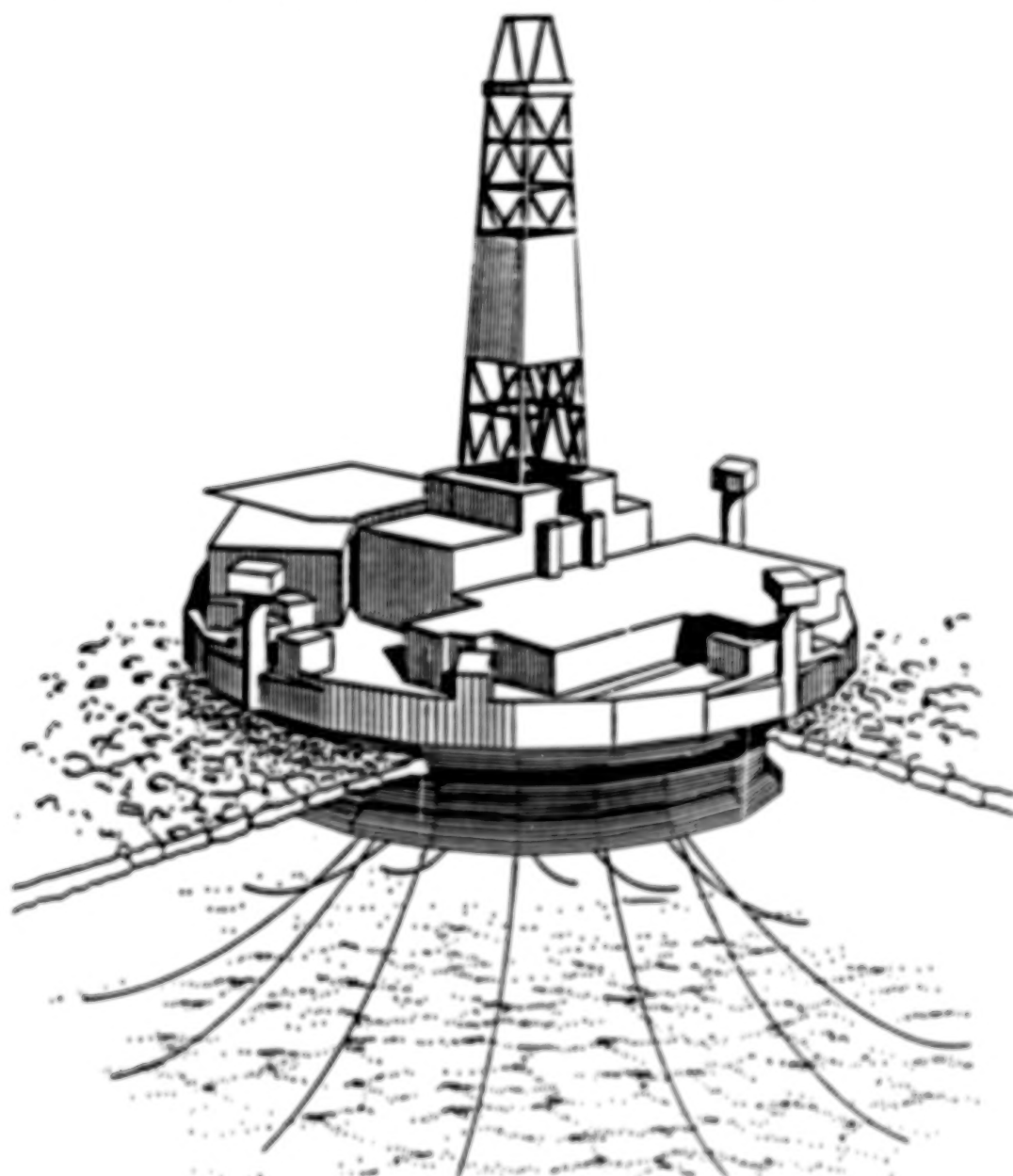


Figure 1 — Cable Moored Platform Similar to "Kulluk".

However, while "Kulluk" has operated with success, there remain to be answered a number of concerns for the designers and operators of such platforms. Obviously of importance are the forces and dynamic response of the platform as it encounters a variety of different ice types. Knowledge of the dynamic response "envelope" of a platform will enable more effective decisions regarding emergency movement of the platform to be made.

Another area of concern is the problem caused by ice under-riding the platform and potentially damaging the drillstring. Indeed, this may be the most important factor in determining safe operating conditions for the platform.

In order to examine more fully the behavior of cable moored platforms in ice infested waters, a series of model tests were performed using the Iowa Institute of Hydraulic Research (IIHR) Ice Towing Tank (see Figure 2). A 1:45 scale model of a conical cable-moored platform (shown in Figure 3) was used in the tests, and impact velocity, ice strength and heave, pitch and surge restoring forces were appropriately scaled.

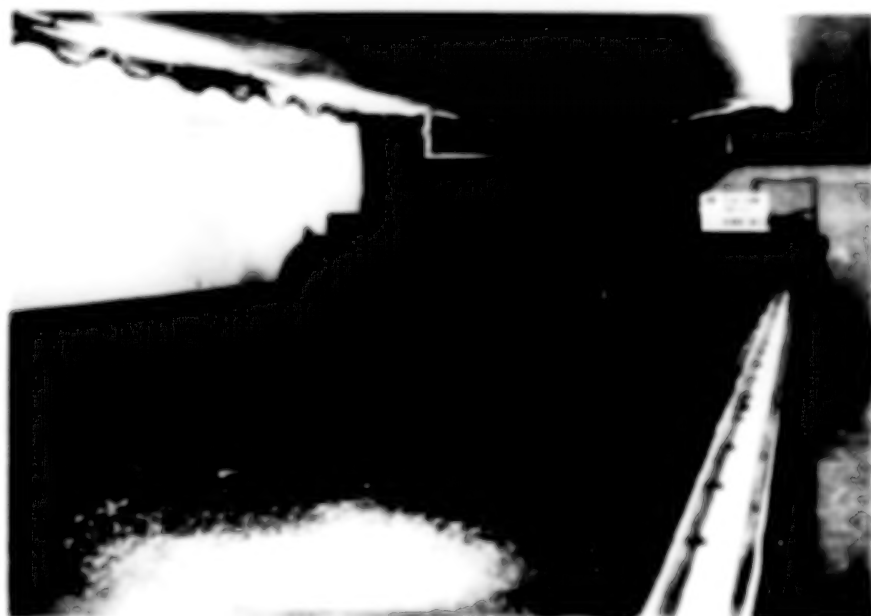


Figure 2 — IIHR Ice Towing Tank.



Figure 3 — The Model Platform.

Two ice conditions were examined. First, sheets of ice of varying thickness (20 to 40 mm) were pushed against the platform at velocities between 0.2 and 0.02 ms^{-1} . Two "mooring" conditions of the platform were used in this experiment. In the first condition it was fixed and could not move as a result of ice impact. For this case forces in the surge and heave direction, and the pitch moment, were measured. The second condition was termed "moored". In this case, the platform could surge heave and pitch (though it was constrained from yawing, rolling, and swaying). The mooring cable resistance was modeled by a leaf spring assembly, and restoring forces to heave and pitch motion were provided by the buoyancy of the platform. Two displacement transducers and three accelerometers were mounted on the platform. The instrumented platform is shown in Figure 4.



Figure 4 — Instrumentation on the Platform.

A total of 42 tests were conducted for ice sheet impact with the platform. Fifteen of these were for the "fixed" platform; 7 for the moored platform with a mooring stiffness (model) of 1.7 kN/m and 20 for the moored platform with a stiffness of 0.5 kN/m.

Both moored and fixed platforms experienced increasing surge force with increasing ice thickness (see Figure 5, which shows only one ice strength and one ice velocity condition). It can be seen that the forces on the fixed platform are somewhat greater than for the moored platform. Note that mean force values and mean values plus two standard deviations are shown on the graph. For the fixed platform, heave force and pitch moment show the same trend with ice thickness, as do heave displacement and pitch angle for the moored platform. The effect of ice velocity on forces and displacements is to some extent masked by experimental scatter, and, thus, no clear trends are apparent.

A dynamic (fourier) analysis of the recorded time series was made. From this analysis it was apparent that the dominant frequency for the fixed platform response was the breaking frequency of the ice. This was also true for the pitch angle and heave displacement of the moored platform. However, the surge force response of the moored platform was dominated by the natural surge frequency of the ice.

Two other important results were found in this part of the study. First, the surge force experienced by the platform exhibited a minimum with mooring stiffness (see Figure 6). This suggests that it may be possible to adjust mooring cables on a platform so as to minimize forces on the platform, and this is being further explored in the 1988 project. The other result of importance was that significant amounts of ice were forced under the platform during each interaction event. This suggests that design of the platform "skirt" must be adjusted to minimize such subduction events.

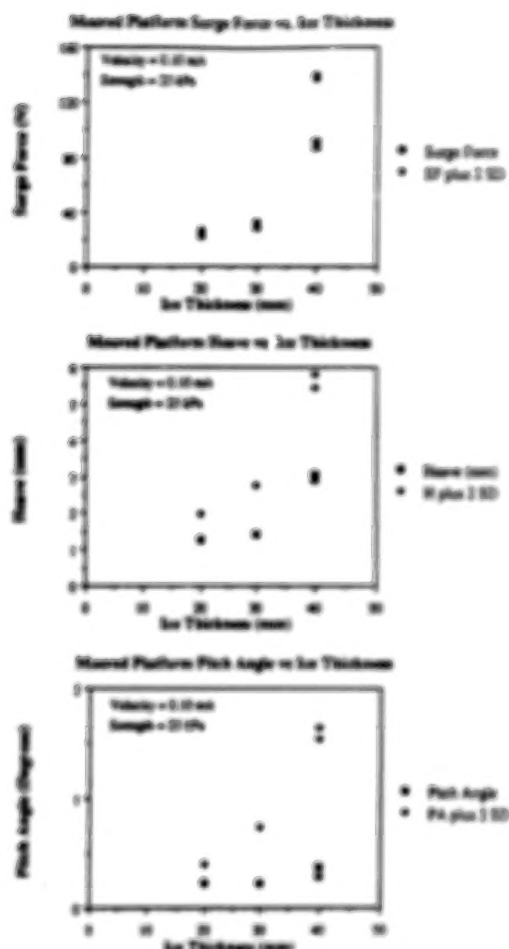


Figure 5 — Representative Results: Ice Sheet Tests, Surge Force vs. Ice Thickness.

The second ice condition examined was that of rubble ice. Rubble ice was formed in the test tank by growing a number of sheets to the required thickness (5 mm and 25 mm), then breaking up the sheet and storing the broken fragments under insulation until sufficient rubble had been formed for testing.

Thirty-two tests were performed at three rubble layer thicknesses (single-layer thick, 50 mm thick and 100 mm thick) and at four impact velocities between 0.02 and 0.20 ms⁻¹. Figure 7 shows a test in progress. Tests were only performed on the "moored" platform configuration.

At all velocities, surge force increased with increasing layer thickness, as did the heave displacement. The mean angle of pitch appeared to show a maximum with layer thickness, possibly because of resonance effects (see Figure 8). The displacements and loads did not achieve a steady state, as shown in Figure 9, which is in contrast with previous work by Matsuishi and Ettema. This is because, rather than a stable "prow" of ice forming and remaining in front of the platform, a prow would form, be stable for a while (the flat part of the curve in Figure 9), then slough off causing the load to rise.

As in the tests on sheet ice, scatter masks any trends of forces or displacements with impact velocity. Certainly there is no strong dependence on the surge force or the heave and pitch displacement on the velocity.

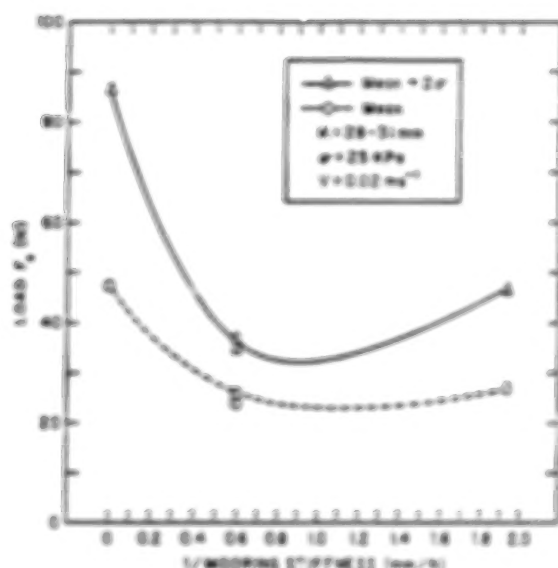


Figure 6 — The Effects of Mooring Stiffness on Surge Force.



Figure 7 — Rubble Ice Test in Progress.

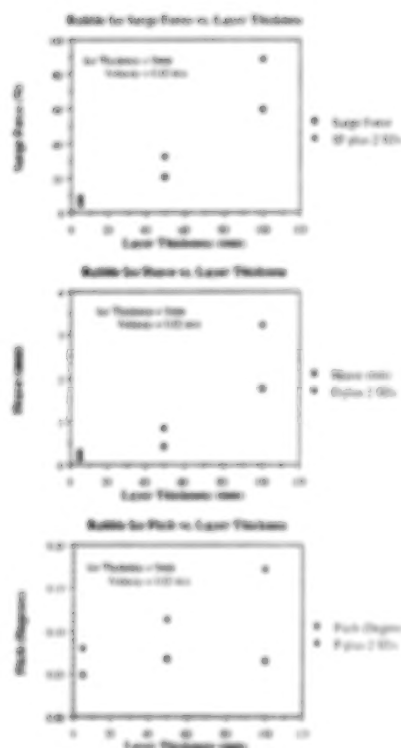


Figure 8 — Representative Results: Rubble Ice Tests, Surge Force, Heave and Pitch vs. Layer Thickness.

Conclusion

Scale-model testing has shown that the most significant factor in determining loads on a cable moored platform in ice is the thickness of the ice, regardless of whether the ice is a single monolithic sheet or in the form of a rubble field. Also of importance is the mooring system stiffness. The dynamics of the ice: interaction process are dominated either by the breaking frequency of the ice or, for the surge forces only, by the natural surge frequency of the platform.

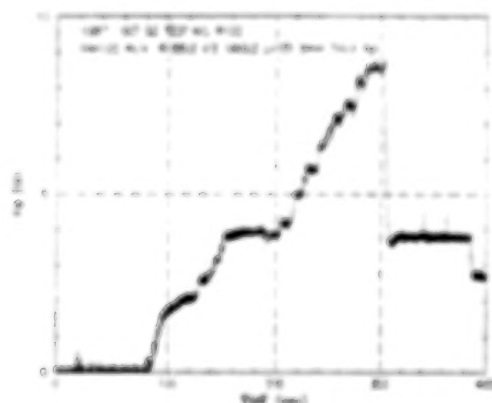


Figure 9 — Time History for Rubble Ice Test.

Blast Effects on Marine Life from Explosive Removal of Platform Legs

Principal Investigator: Joseph G. Connor, Jr.
Explosion Dynamics Branch
Naval Surface Warfare Center
Silver Spring, MD

Objective: To determine the effects of oil rig leg severance explosions on marine life.

Oil drilling platforms that have served their purpose must be removed from navigable waters. Left in place, they present obstructions to general navigation as well as to net fishing operations. The process of removal is most efficiently begun by explosively severing the legs some distance beneath the ambient bottom. An explosive charge is detonated inside the hollow pilings and risers that descend into the seabed. The explosive severance operation should be carried out with little or no debilitating effect on local marine life.

Detonation of an explosive underwater produces sudden changes in ambient conditions as energy is released and propagates away from the detonation site. The effect of the explosion is measured by the amplitude and duration of over- and under-pressure pulses and the rate at which energy and momentum are transported away from the explosion (Cole, 1948).

Damage to a nearby object depends strongly on the structural details of the object and its surroundings. Some objects are damaged by a sharp increase in pressure beyond a critical threshold level; others, simply by the push delivered by the explosion shock impulse.

If the impulse is delivered in a period of time, approximating the period of natural vibration of the object, resonant vibrations occur. Vibration amplitude increases, usually with consequent severe damage. Such resonances appear to be the dominant damage mechanism for biological specimens containing gas-filled cavities. Examples are the swim bladders in certain fish, the lungs in air breathing mammals, and the various tissues that contain small pockets of gas in many other creatures (O'Keeffe, 1984).

A scientific program had been devised to define the blast pressure signatures associated with the explosives used by the industry for platform removal and to examine the impact of these pressures on sea turtles. However, the program has been modified because of two unforeseen circumstances. The Navy has been restricted from detonating explosives in its test areas of the lower Potomac River and Chesapeake Bay. Other sites have been examined but none, which are available, are suitable for this experiment where a soft bottom and long horizontal range are necessary. In addition, the use of sea turtles for test purposes has been forbidden by Federal authorities. Though at some point these scientific data should be attained, for the purposes of allowing the industry to continue their operational use of explosives, an interim solution is being sought.

It is highly likely that authorities will permit *in situ* blast removal of platforms under controlled conditions. These stipulations include detonations of 50 pounds of explosives, 3 m below the mudline, inside a platform leg or riser. In addition, the tests would have to be begun in daylight, and preceded by the underwater examination and clearance of the test area of any turtles. The Navy will work cooperatively with the industry to string its pressure sensing array (which has horizontally and vertically spaced pressure sensors) from the platform to a vessel where data will be recorded. Figure 1 shows the configuration. It is quite likely that the monitoring vessel will be a floating derrick used for removal operations. It is also likely that Composition C-4, Composition B, and probably nitromethane will be the explosives tested.

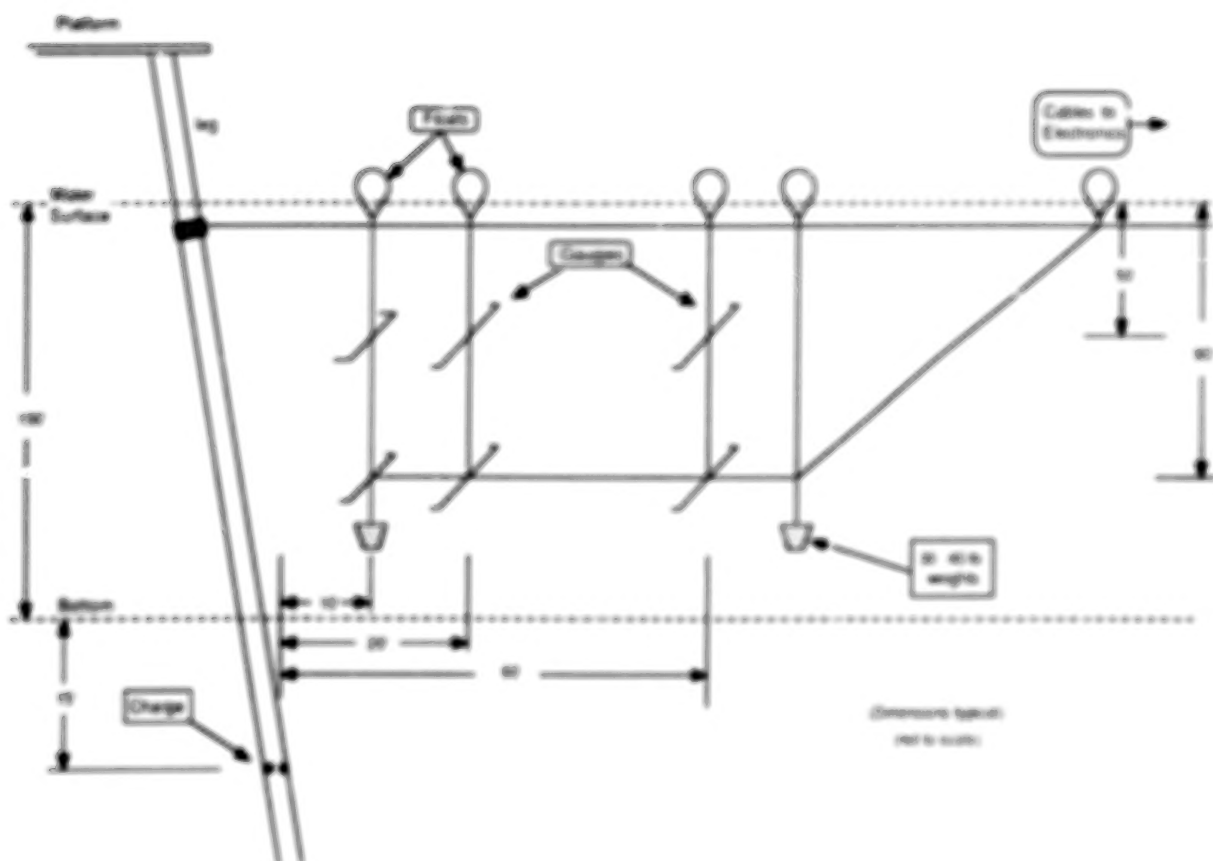


Figure 1 — Pressure Sensing Array Configuration.

The experiment probably will not measure free, midwater detonations to gather baseline data nor will it include turtles, but, instead, will provide useful information on the pressure signatures which can be expected for the types of tubulars and explosives tested.

It is expected that the program can be accomplished during the latter months of 1988.

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Flow-Induced Vibration of Risers and Cables in a Sheared Flow Current

Principal Investigator: Professor J. Kim Vandiver
Massachusetts Institute of Technology
Room 5-222
Cambridge, Massachusetts 02139

Objective: To investigate the behavior of risers and cables subject to large sheared flow currents.

The prediction of the flow induced vibration response of long cylinders, deployed in sheared flows, is a problem of great practical importance. The applications vary from extremely long cables that exhibit the dynamic behavior of systems of infinite length to relatively short and stiff risers, conductors, and pipelines, which respond to vortex shedding in only a few of the lowest natural modes of vibration. Recently, considerable attention has been given to the use of compliant production risers. These hose-like cylinders are usually deployed with rather low tension and are thought to be rather highly damped. However, there is relatively little known about their response under vortex shedding conditions. One of the objectives of this research project was to investigate the response of low tension hoses, as high tension cylinders.

Field experiments have been conducted on the vortex-induced vibration of cables and risers since 1975. In the early tests the emphasis was on the study of the vibration response of cylinders in uniform flow. Resonant lockin was the phenomenon of greatest interest and concern at the time. Lockin typically resulted in response amplitudes of ± 1 diameter. By the summer of 1986 the state of the art had reached the point that response prediction models were being sought for risers in sheared flows as opposed to uniform flows. Sheared flow causes vibration response, which includes the simultaneous response of many natural modes.

A research project was conducted on the flow-induced vibration response of cables and risers in sheared flows. The research work began with an experiment in the summer of 1986 in which an experimental cylinder was tested in a controllable sheared flow. The results of the experiments quickly revealed the importance of hydrodynamic damping in the control of flow-induced vibration. Hydrodynamic damping had not historically been of concern when considering resonant lockin response in uniform flows but it was discovered to be of unusual importance in regulating the response of cylinders in sheared flows.

The data from the experiment was used to develop a response prediction model for sheared flow conditions. In the remainder of this report, the experiments are described, the damping model is introduced, the response prediction model is described, and predictions are compared to measured field data.

Experiments were conducted during the summer of 1986. The test site was a mill canal built in 1848 in Lawrence, Massachusetts. A dam diverts water from the Merrimack River into the canal. The flow is controlled by four vertical, submerged, bottom opening gates, which are spaced at equal horizontal intervals in a gatehouse at the head of the canal. By controlling the various gate openings a sheared flow can be developed horizontally across the width of the canal, which is approximately 58 feet. The test cable location was approximately 250 feet down stream of the gatehouse. The cable was tensioned horizontally across the width of the canal about 1 foot under the surface of the water, as shown in Figure 1. Heavy steel pipe supports transferred the cable loads to the walls of the canal. Tension was applied to the cable via a system of pulleys and a hand operated winch.

Five feet upstream of the test cable a simple traversing mechanism was constructed to carry an acoustic current meter to any position between the canal walls. The current profiles were measured prior to response tests. The results of three different profiles are shown in Figure 2. The steepest profile was approximately linear with a peak flow velocity of 4 feet per second and a minimum flow velocity of -0.5 feet per second. Minus indicates a flow reversal. A milder shear flow was generated which ranged approximately linearly from 2 feet per second down to zero. A third profile was generated which was as close to uniform as possible.

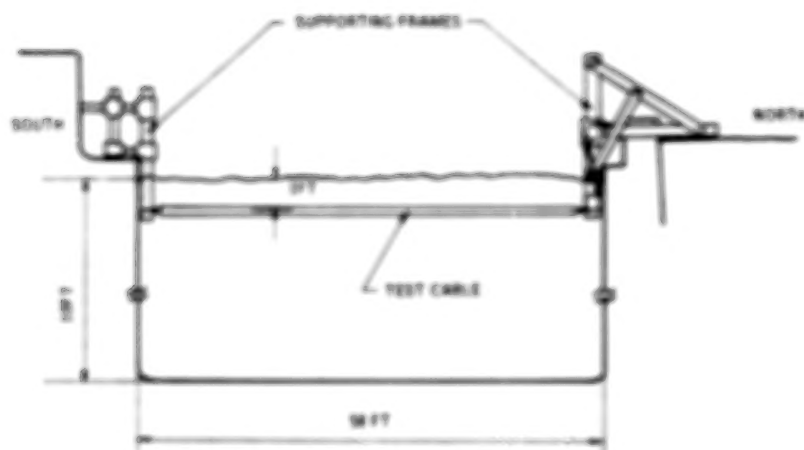


Figure 1 — Shear Flow Test Configuration.

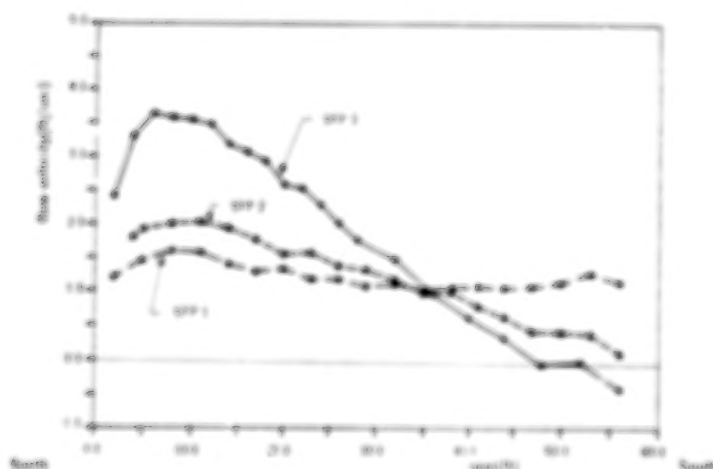


Figure 2 — Measured Current Profiles.

The flow at all times was highly turbulent with the RMS turbulence level varying from 10% to 20% of the mean of the profile. An important conclusion is that the turbulence did not alter greatly the vibration of the cable when compared in a subjective way to other experimental results such as those made in earlier years at Castine, Maine. The turbulence did, however, make the vibration response have a broader frequency bandwidth and prevented pure tone lockin from occurring even when the cable was deployed in the nearly uniform profile.

The 58 foot long test cable is shown in Figure 3. It consisted of a 1.125 inch outside diameter, rubber hose with a 0.5 inch inside diameter. Seven 0.16 inch diameter, braided, kevlar cables were carried inside the hose providing the strength. Each kevlar cable had 7 conductors inside of it. Six biaxial pairs of force balance accelerometers were placed on the centerline of the cable at locations shown in the figure.

The twelve accelerometer outputs, tension, and current data were carried via a multi-conductor cable from the test cable to the gate control house where a computer data acquisition system was located.

On a cylinder in a flow lift forces are generated by vortex shedding. The frequency of the lift forces is proportional to the flow velocity. Therefore, in a sheared flow profile the vortex shedding frequency and hence the lift force frequency varies along the length of the cylinder in relation to the variation of the flow velocity along the cylinder. As a consequence of this, the lift force frequency will coincide with different natural frequencies at different spatial locations along the cylinder, depending on the variation in vortex shedding frequency. This is depicted in Figure 4, which shows a sheared flow profile encountering a cylinder. The figure depicts a region where the second natural frequency is coincident with the local vortex shedding frequency. In this region power is injected into the cable at the second natural frequency, and outside of this region the fluid provides a net damping or a source of power flow out of the cable for vibration at the second natural frequency.

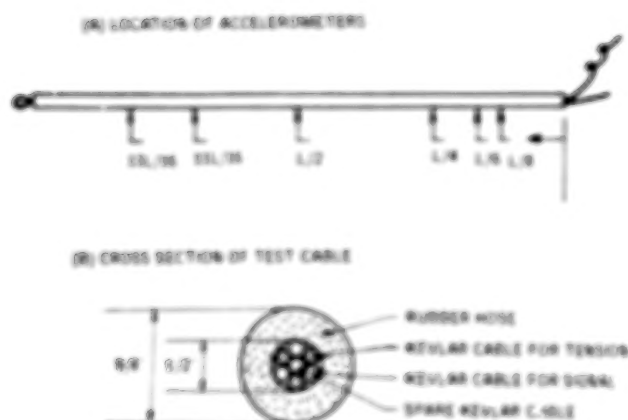


Figure 3 — Test Cable Construction.

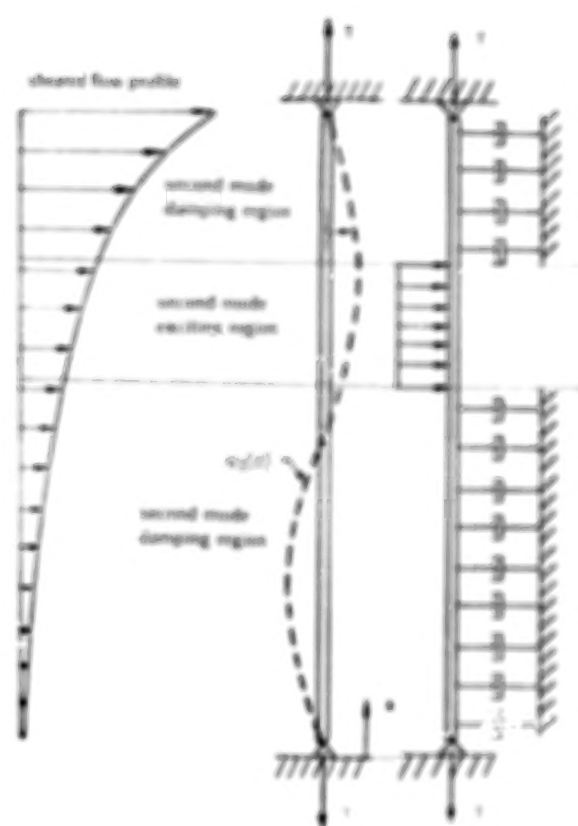


Figure 4 — Regions of Fluid Damping and Excitation.

This is quite different from uniform flow lockin conditions in which the vortex shedding frequency is synchronized with the natural frequency over the entire length, leaving no substantial region for hydrodynamic damping to play a significant role. Under sheared flow conditions the regions, which do not coincide with the particular natural frequency of interest, are significant sources of hydrodynamic damping. In the experiments the amount of hydrodynamic damping was measured and it was also predicted on the basis of models which are described in Vandiver and Chung (1987).

A particular example will be used in the rest of this report in which the lowest natural frequency of the test cable was about 0.92 cycles per second, and the cable was exposed to the moderate shear flow profile, which varied linearly from zero to about 2 feet per second. The corresponding vortex shedding frequency varied from zero up to about 4 cycles per second over the span of the cable. The first, second, third, and fourth mode each had regions where it was driven by the vortex shedding process. The structural damping of the cable measured in air by transient decay tests was less than 0.3% of critical damping for these modes. The hydrodynamic damping for this cable varied from approximately 24% for the first mode, decreasing 4.5% for the fourth mode. Hydrodynamic damping in this experiment was the controlling damping mechanism for this cable.

In this research a method for predicting the response of cables in sheared flows was developed. The prediction model includes the effects of correlation length, hydrodynamic damping, lift coefficient with higher order harmonics and turbulence. This model is completely described in Chung (1987), Vandiver and Chung (1988). One example is given here. The test cable had a tension of 349 pounds, and a specific gravity of 1.34. The shear flow profile used in the prediction varied linearly from zero to 2 feet per second. The model was used to predict the acceleration response spectrum at two locations on the cylinder. The two locations, specified as fractions of the length measured from one end were at $L/8$ and $13L/16$, thus giving locations that are on extreme opposite ends of the cable. The response location at $L/8$ is in the high flow velocity region of the shear. The other response location is in the low flow velocity region. The details of the response prediction model are not given here but example results are shown in Figures 5, 6 and 7. Figure 5 shows the predicted acceleration spectrum at the two locations. The pre-

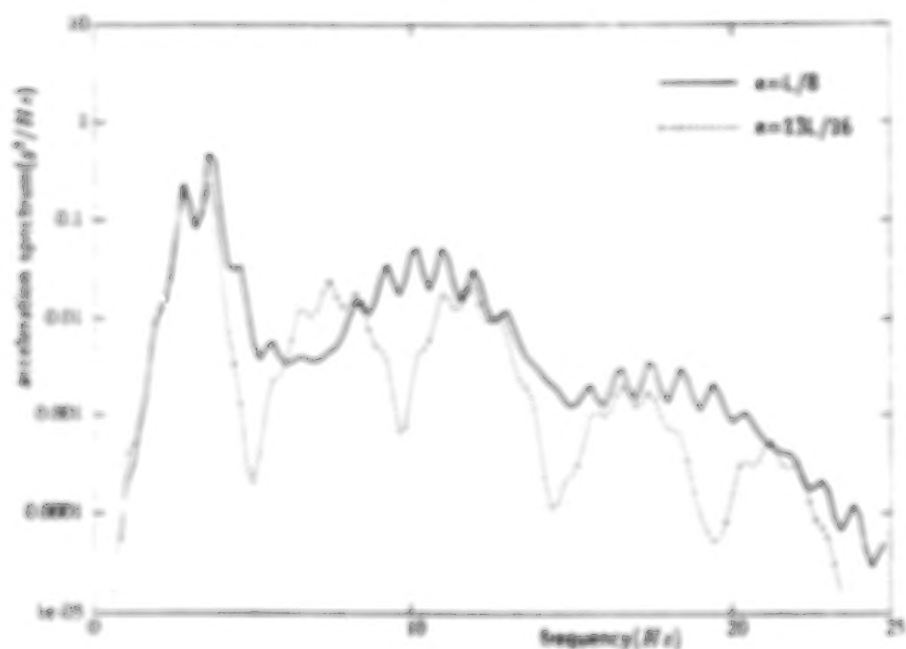


Figure 5 — Predicted Acceleration Spectrum at L/8 and 13L/16 for the Mild Shear Case.

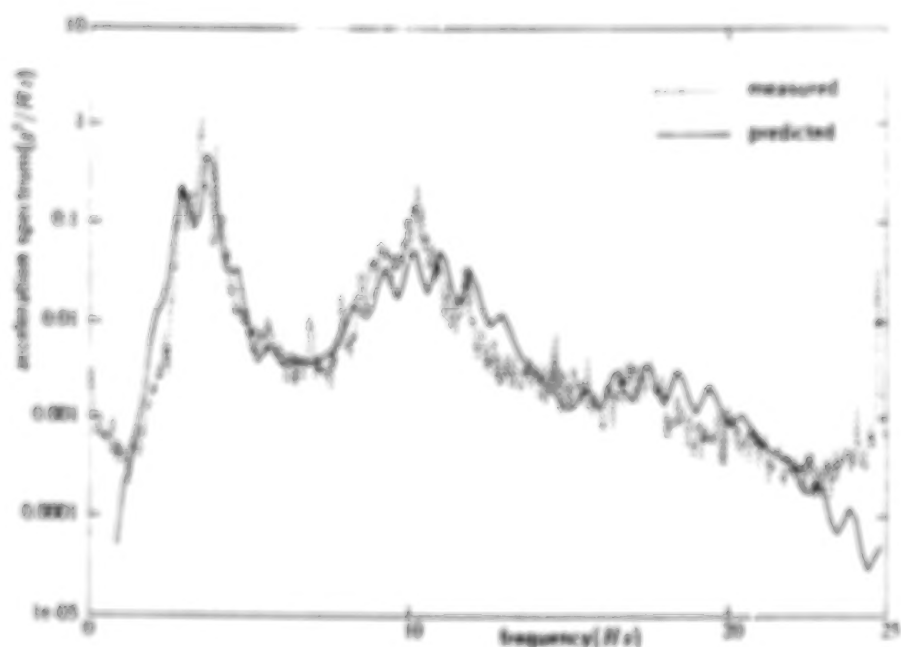


Figure 6 — Comparison of Predicted and Measured Response at L/8.

dicted responses are different, primarily because of the effects of damping. Figure 6 shows both the predicted and measured response of the cable at position L/8, and Figure 7 shows the comparison between predicted and measured response at 13L/16. The agreement is quite good. In these cases the predicted and measured RMS displacement responses were approximately 0.5 diameters for both locations.

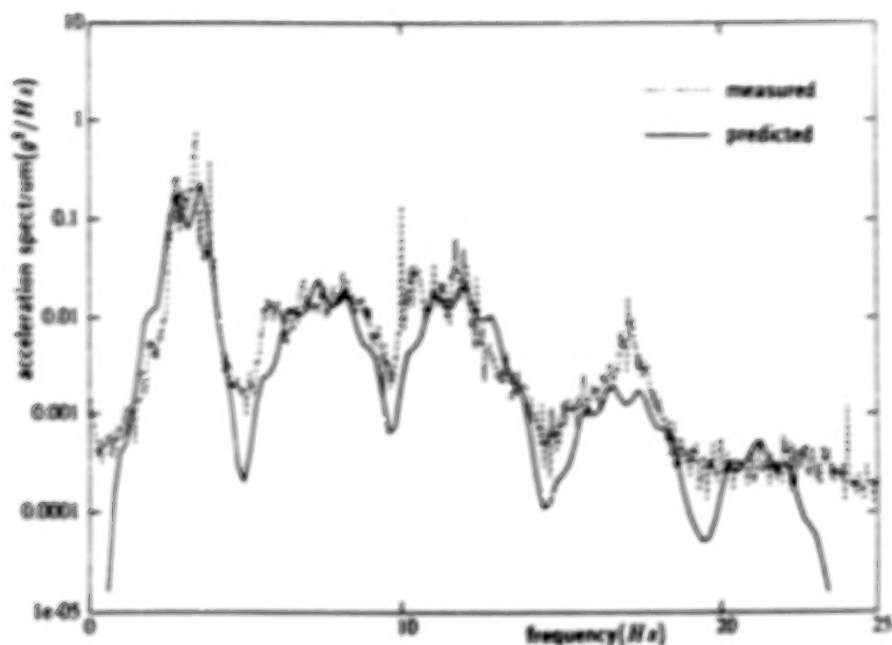


Figure 7 — Comparison of Predicted and Measured Response at 13L/16.

The objectives of the continuing research are to enhance the response prediction techniques to be able to handle more general problems such as cylinders with spatially varying tension and bending stiffness. Fatigue is an important consideration for offshore applications such as tension leg platform tension members, production risers and conductors. The prediction of fatigue life requires knowledge of not displacement or acceleration response spectra but knowledge of stress spectra at important locations. One of the objectives of the new research project is to formulate response prediction tools so as to produce results directly in terms of stress spectra.

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A New System Identification Technique Based on the Random Decrement Signatures for Damage Detection

Principal Investigators: Dr. Jackson C.S. Yang
University of Maryland
College Park, Maryland 20742

Dr. Nabih E. Bedewi
Advanced Technology & Research Corp.
14900 Sweitzer Lane
Laurel, Maryland 20707

Objective: To experimentally demonstrate and verify the applicability of a system identification technique based on Random Decrement signatures for modeling and damage detection in large structures.

Identification of the system parameters of a randomly excited structure may be treated using a variety of statistical techniques. Of all these techniques, the Random Decrement is unique in that it provides the homogeneous component of the system response. Using this quality, a system identification technique was developed based on a least-squares fit of the signatures to estimate the mass, damping, and stiffness matrices of a linear randomly excited system. The mathematics of the technique were presented by the principal investigators in Bedewi and Yang (1987) in addition to the results of computer simulations conducted to demonstrate the prediction of the response of the system and the random forcing function initially introduced to excite the system. The results of an experiment conducted on an offshore platform scale model to verify the validity of the technique and to demonstrate its application in damage detection is presented.

Given a randomly excited linear multidegree-of-freedom system, response data is obtained at several locations. A model for the system is assumed in the form

$$[M]\ddot{X} + [C]\dot{X} + [K]X = F \quad (1)$$

where $[M]$ and $[K]$ are real symmetric matrices representing the mass and stiffness of the structure, $[C]$ is a nonproportional, real, symmetric damping matrix, F is the forcing vector, and X and its time derivatives represent the response of the system. Random Decrement and cross-Random Decrement signatures are then obtained from the response data thus forming the homogeneous components of the response. Substituting the signatures in Equation (1) and noting that vector F is zero, a least squares fit is then performed with the assumption that one of the elements in the system matrices is known.

A 1:13.8 scale model of an offshore platform structure was set up on outdoor earth ground. The base of the structure was welded to a steel (box type) frame, then both were lowered into a 6'x6'x3' pit hole. The pit was then filled with wet concrete up to the base of the structure and left to cure.

The model structure consists of four legs made of 2" diameter, 0.25" wall, steel pipes. Figure 1 shows the configuration of the structure with its dimensions and labeled points. A pendulum was set up to provide random impact excitation at point 13. The responses at points 1 to 13 were monitored using accelerometers screwed into threaded aluminum blocks attached directly to the structure.

The first experiment was conducted to verify the reliability of the system identification technique in obtaining a model from Randomdec signatures. To accomplish this task, the response of the structure, as well as the input to the structure, had to be measured.

Four accelerometers were mounted at locations 4, 6, 8, and 13, and a load cell was firmly attached to the tip of the pendulum hammer. The structure was randomly impacted for 20 seconds while the output of the five transducers was recorded on analog tape simultaneously. The five channels were then digitized at a sampling rate of 1000 Hz after passing through a low pass filter set at 125 Hz. The cutoff frequency of the filter was selected based on a maximum system frequency of interest of 85 Hz.

The time record at location 13 was used for triggering the signatures. Figure 2 shows the Randomdec signature for location 13. The system identification technique was then employed in conjunction with the signatures to calculate the 30 unknown parameters in the $[M]$, $[C]$, $[K]$ matrices. Four sets of matrices

were initially calculated, each set corresponding to one fixed element in the stiffness matrix. The four sets of matrices were then averaged to obtain the best estimate for the model.

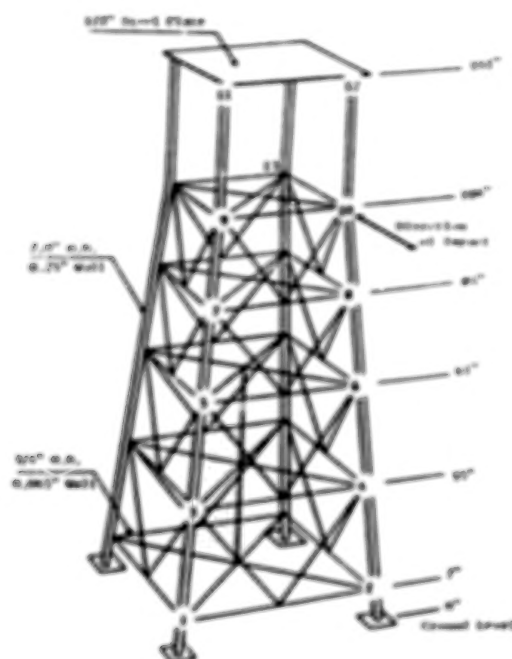


Figure 1 — Configuration of Offshore Platform Scale Model.

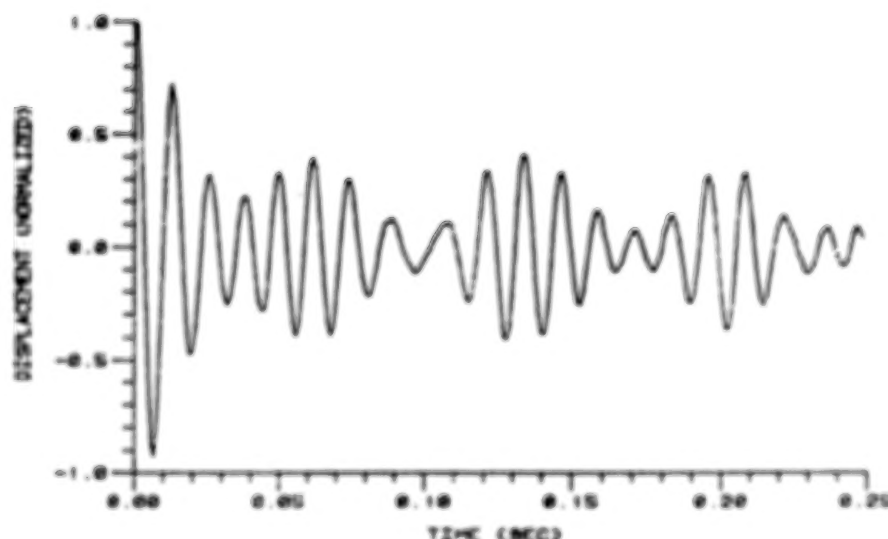


Figure 2 — Randomdec Signature of Time Response at Location 13.

To confirm the accuracy of the established model, the three system matrices were substituted into the set of differential equations describing the system, Equation (1), and the second derivative of the load applied during the experiment introduced as input (the derivative is taken since the signatures were obtained from acceleration records). The initial conditions were extracted from the measured response of the system, and Equation (1) solved numerically. A step size of 0.001 sec. was used corresponding to the time step of the sampled data.

Since the estimated system parameters were not originally scaled to match the actual system in magnitude, the response had to be scaled to facilitate the comparison. This was performed by multiplying the estimated responses at the four points by the average of the ratios of the standard deviations of the measured responses to the standard deviations of the estimated responses. Furthermore, all the responses

were multiplied by -1 since they appeared to be mirror images of the actual responses about the time axis. This change in sign is a legitimate step since the same effect could have been achieved by scaling the system matrices by -1.

The results of the comparison at point 4 are shown in Figure 3. The plots indicate that the predicted system response is in good agreement with the actual response.

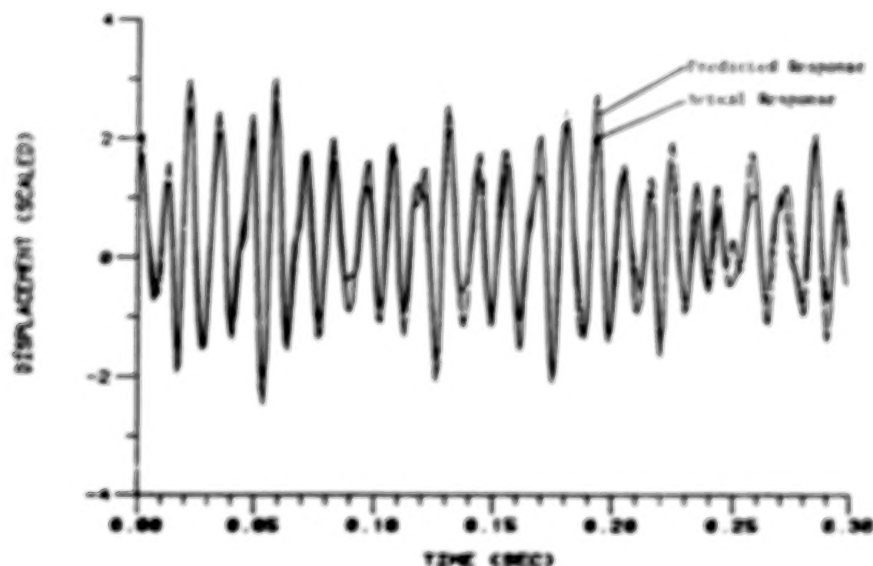


Figure 3 — Comparison of Measured vs. Predicted Responses at Point 4.

Another approach to verify the accuracy of the model is to compare the measured force with the predicted force. Therefore, the measured system response was substituted in Equation (1) with the three estimated matrices and the force vector calculated. Again, the output was scaled for comparison. Figure 4 shows the predicted force time record and the second derivative of the measured force time record at location 13. The forces are in good agreement when a force is being applied, but some large oscillation exists in the predicted record when no force is actually being applied. Careful inspection of the figure reveals that the oscillations have a frequency of 125 Hz, corresponding to the frequency of the filter. Figure 5 shows a comparison of the forces at locations 4, 6, and 8. The magnitude of the predicted forces is small relative to the force at point 13 (these records were already scaled using the scaling factor employed at point 13).

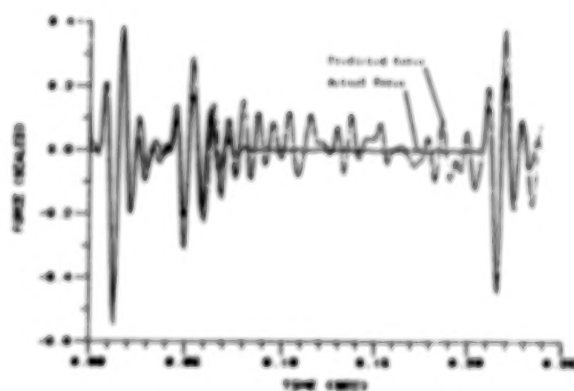


Figure 4 — Comparison of Measured vs. Predicted Forces at Point 13.

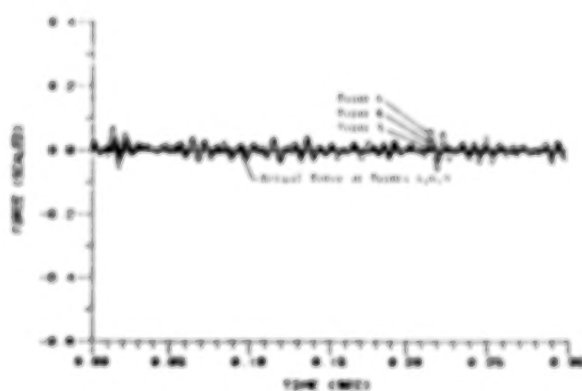


Figure 5 — Comparison of Measured vs. Predicted Forces at Points 4, 6, and 8.

A useful application for the system identification technique is the detection of changes in the system parameters resulting from induced damage. A large crack in a structure would decrease the local stiffness, thus reducing one or more of its natural frequencies. On the other hand, a corroded section of the structure might reduce the localized mass as well as the stiffness. Therefore, by calculating the system matrices consistently and comparing them to the matrices of the originally perfect system, the occurrence of a damage, and possibly its identity, might be detected.

Although this approach for a damage detection criterion is theoretically feasible and effective, it is not easy to implement in practice. The difficulty arises in interpreting the changes in the system model and in being able to connect the different changes with the types of damages that could have resulted in their occurrence. In addition, it is possible that some parameters are more meaningful than others in this application. For example, the diagonal elements in the mass matrix are more sensitive to changes in the mass at their respective locations than the off diagonal elements.

The stiffness matrix is somewhat more difficult to analyze than the mass matrix. From the point of view of damage detection, it is more appropriate to observe changes in the flexibility matrix than the stiffness matrix. This can be easily verified by considering the static equations describing a multidegree-of-freedom system, namely

$$[K] X = F \quad (2)$$

Defining the flexibility matrix as $[A] = [K]^{-1}$, Equation (2) becomes

$$X = [A] F \quad (3)$$

Assuming the system to have three degrees-of-freedom, Equations (2) and (3) may be expanded as follows:

$$\begin{aligned} k_{11} x_1 + k_{12} x_2 + k_{13} x_3 &= f_1 \\ k_{21} x_1 + k_{22} x_2 + k_{23} x_3 &= f_2 \\ k_{31} x_1 + k_{32} x_2 + k_{33} x_3 &= f_3 \end{aligned} \quad (4)$$

and

$$\begin{aligned} x_1 &= a_{11} f_1 + a_{12} f_2 + a_{13} f_3 \\ x_2 &= a_{21} f_1 + a_{22} f_2 + a_{23} f_3 \\ x_3 &= a_{31} f_1 + a_{32} f_2 + a_{33} f_3 \end{aligned} \quad (5)$$

It is clear from Equations (4) that k_{ij} represents the force at point i when $x_i = 1$ and $x_k = 0$ where $k \neq j$. This is rather difficult to visualize in a complex system. On the other hand, it can be seen from Equation (5) that a_{ij} represents the deflection at point i when a unit load is applied at point j . Besides being more physically realizable, any element a_{ij} may be meaningfully treated separately.

The next issue to be addressed is the significance of the diagonal and off-diagonal elements in the flexibility matrix. It has been traditionally accepted that only the diagonal terms need to be considered since they strongly reflect the absolute flexibility of their respective locations. This is not necessarily the most effective approach though. To demonstrate that off-diagonal elements are a better indication of the flexibility at a point, consider the system shown in Figure 6a. The beam is of length L and is rigidly attached at both ends. If three equidistant points are monitored on the beam, the resulting flexibility matrix could be found using simple "strength of materials" tables to be:

$$[A] = \begin{bmatrix} 2.197 & 2.604 & 1.058 \\ 2.604 & 5.208 & 2.604 \\ 1.058 & 2.604 & 2.197 \end{bmatrix} \frac{10^3 L^3}{EI}$$

where E is Young's modulus of the material and I is the cross-sectional area moment of inertia of the beam. Now, taking the extreme case, suppose that the beam was cut at some point between locations 1 and 2, resulting in two cantilever beams of unequal lengths (Figure 6b). The new flexibility matrix of the damaged system is

$$[A]^d = \begin{bmatrix} 5.208 & 0.000 & 0.000 \\ 0.000 & 41.667 & 13.020 \\ 0.000 & 13.020 & 5.208 \end{bmatrix} \frac{10^9 L^3}{EI}$$

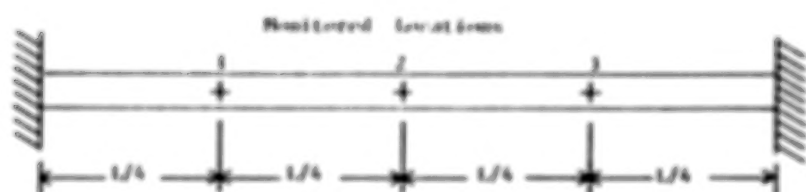


Figure 6a — Configuration of Undamaged Fixed-Fixed Beam.

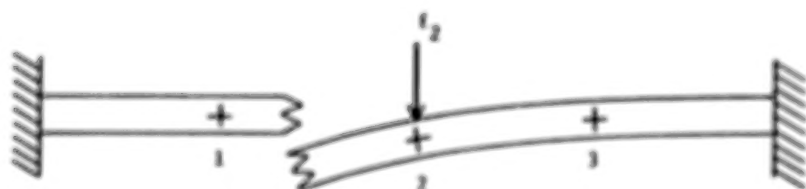


Figure 6b — Configuration of Damaged Fixed-Fixed Beam. Separation Into Two Cantilever (Fixed-Free) Beams.

A matrix $[R]$ may now be constructed where each element r_{ij} is defined as

$$r_{ij} = \frac{a_{ij}^d}{a_{ij}}$$

namely

$$[R] = \begin{bmatrix} 2.371 & 0.000 & 0.000 \\ 0.000 & 8.000 & 5.000 \\ 0.000 & 5.000 & 2.371 \end{bmatrix}$$

Graphing the diagonal terms as a function of point location (Figure 7a), and noting that the beam ends have a ratio of 1, it would be deduced that the damage occurred at point 2 due to the symmetry. On the other hand, if the off-diagonal elements of the adjacent points are plotted between the two points they represent (Figure 7b), the damage would be correctly identified as being between 1 and 2. It is of vital importance to note that for diagonal terms the steepest peak represents the damage whereas for off-diagonal terms the steepest valley represents the damage. This is because a load applied at a point next to the damage would cause the point to deflect more than it did before the damage was introduced, whereas the point on the other side of the damage would deflect less than it did before the damage was introduced.



Figure 7a — Plot of Flexibility Matrix Diagonal Elements.



Figure 7b — Plot of Flexibility Matrix Off-Diagonal Elements.

This example may be expanded intuitively to consider the intermediate event where the cut is not severe enough to separate the beam. If the beam is assumed to be composed of two springs, one representing the portion to the left of the damage, and the other the portion to the right, then the deflection on either side of the damage would be indirectly proportional to its respective spring stiffness. In terms of the flexibility matrix ratio, this would mean that the terms which were zero would begin at 1 when no damage exists, then decrease as the damage size increases, until the limiting value of zero is reached when the cut goes all the way through the beam. Conversely, the off-diagonal terms larger than 1 would begin at unity for no damage and finally reach some finite limiting value for the through cut. Figure 7c depicts this process showing the direction of change in the off-diagonal elements. On the other hand, the ratio of the diagonal elements would always result in a symmetric curve regardless of the severity of the damage (Figure 7d).

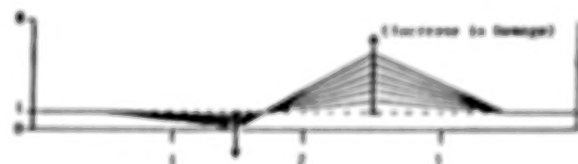


Figure 7c — Transition of Off-Diagonal Elements as Damage Increases.

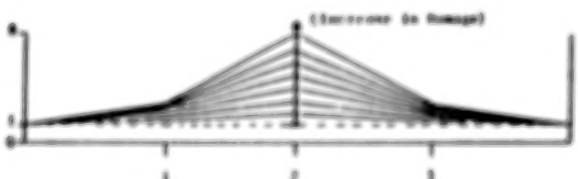


Figure 7d — Transition of Diagonal Elements as Damage Increases.

An experiment was designed and conducted to verify the accuracy of the proposed damage detection criterion. The experiment was composed of two identical parts, one performed before the damage was induced, and the other afterward. To obtain the response of every labeled point on the structure, each part was actually carried out four times. Since four accelerometers were used, one accelerometer was kept at point 10 while the other three were moved to different locations for each run of the experiment. The four sets of monitored points were (1,2,3,10), (4,5,6,10), (7,8,9,10), and (11,12,13,10). The collected data were processed in the same fashion described earlier.

Since station 10 was common for all the sets, it was used for triggering while cross-Randomdec signatures were obtained for the other points. This resulted in four separate Randomdec signatures. The four signatures, shown in Figure 8, prove the repeatability of the technique.

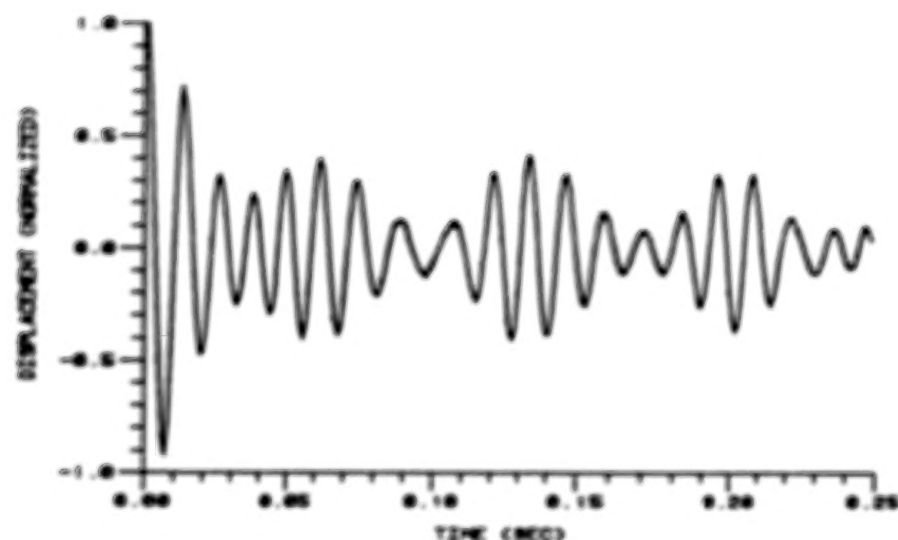


Figure 8 — Comparison of Four Independently Obtained Randomdec Signatures at Location 10.

A through cut was made with a hand saw at the cross member between points 5 and 6. The same process was repeated and twelve cross-Randomdec signatures calculated. Figure 9 shows the Randomdec signatures at location 10 before and after the damage was induced. The changes in frequency and phase are quite apparent.

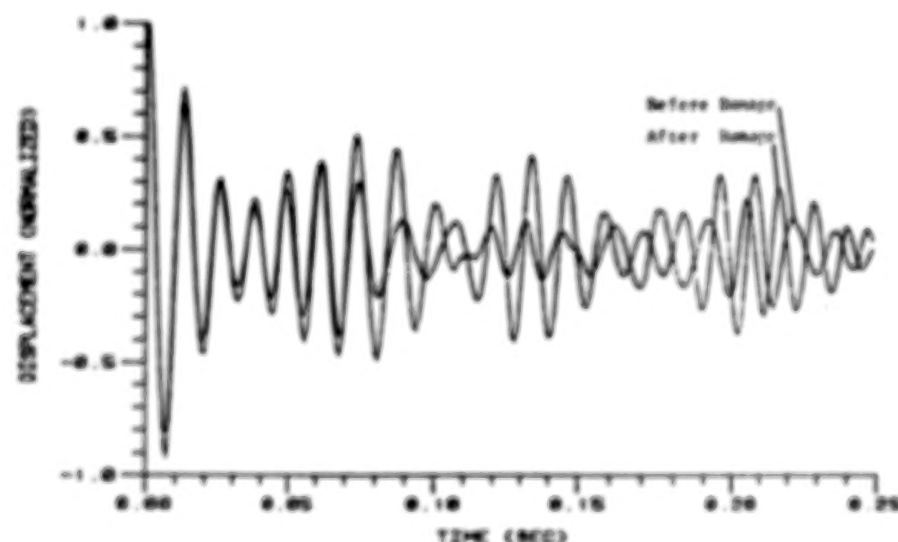


Figure 9 — Change in Randomdec Signature at Point 10 After Damage.

The system identification technique was then used in conjunction with the two pairs of Randomdec signatures at point 10 and the two pairs of eleven cross-Randomdec signatures at points 1 to 9, 11, and 12 to obtain the system parameters before and after the damage. This resulted in two pairs of 12×12 [M], [C], and [K] matrices. The two stiffness matrices were inverted yielding two flexibility matrices, and the ratio of the respective elements taken. Table 1 shows the ratios of the diagonal elements and the off-diagonal elements representing adjacent points. Figure 10 shows the diagonal ratios plotted directly on the structure. It is not clear from the figure where the location of the damage is. The plot of the off-diagonal ratios on the structure is shown in Figure 11. Noting the fact that the lowest ratio indicates the location of the damage, it can be deduced from this figure and from Table 1 that the damage is residing somewhere between points 5 and 6.

Table 1 — Ratios of Flexibility Matrix Elements Before and After Damage.

DIAGONAL ELEMENTS				OFF-DIAGONAL ELEMENTS					
LEG 1 POINTS		LEG 2 POINTS		LEG 1 MEMBERS		LEG 2 MEMBERS		INTERMEDIATE MEMBERS	
Point Number	Ratio	Point Number	Ratio	Member Number	Ratio	Member Number	Ratio	Member Number	Ratio
1	1.02	2	1.16	1,3	3.08	2,4	3.26	1,2	3.62
3	2.67	4	2.29	3,5	1.76	4,6	1.97	3,4	1.16
5	3.91	6	3.27	5,7	0.87	6,8	0.92	5,6	0.13
7	1.86	8	0.06	7,9	0.53	8,10	0.62	7,8	0.50
9	4.64	10	1.64	9,11	2.56	10,12	2.16	9,10	1.04
11	2.29	12	1.09	-	-	-	-	11,12	3.19

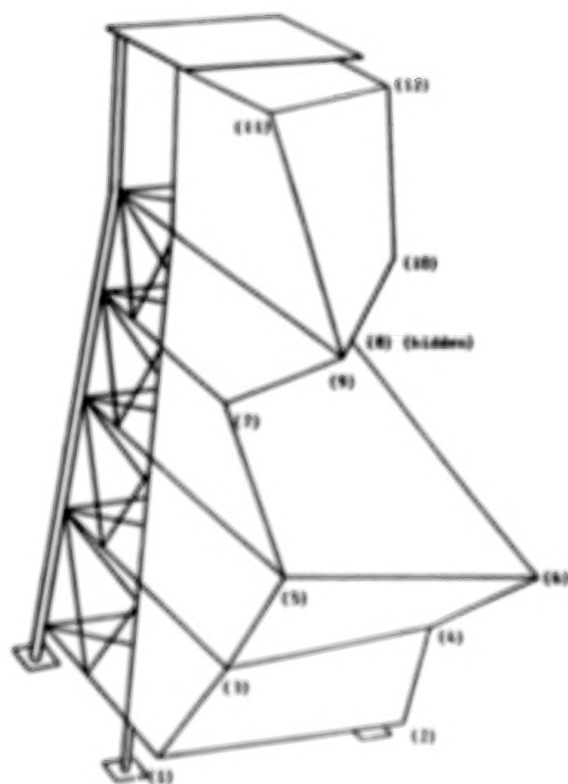


Figure 10 — Plot of Flexibility Matrix Diagonal Elements on Scale Model.

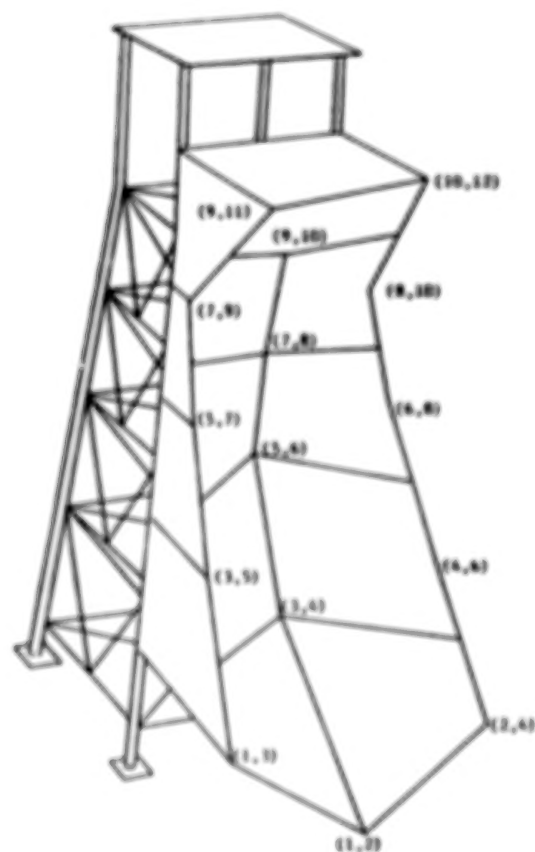


Figure 11 — Plot of Flexibility Matrix Off-Diagonal Elements on Scale Model.

Conclusions

An experiment was conducted on a scale model of an offshore platform structure to verify the applicability of the system identification technique introduced in reference Bedewi and Yang (1987). The technique was employed to obtain a mathematical model of the structure from the random response data. This model was then used to predict the response of the structure and the forcing function initially introduced to excite the structure. These results compared favorably with the measured data.

Finally, an approach for damage detection and location was demonstrated through the inversion and comparison of the stiffness matrix before and after the damage was introduced. The use of a simple example revealed that the off-diagonal elements are more effective in locating the damage than the diagonal elements. The experiment conducted on the scale model of the offshore platform confirmed these findings successfully.

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Quality Control Tests for Weldment Fracture Toughness

Principal Investigator: Dr. Harry I. McHenry
Fracture & Deformation Division
National Bureau of Standards
Boulder, CO 80303

Objective: To review and assess test methods used to measure the fracture toughness of steel weldments, and to recommend methods for quality control purposes.

For offshore structures, many industry standards and company specifications require (or permit) fracture toughness testing to assure satisfactory resistance to brittle fracture. Increasingly, the crack tip opening displacement (CTOD) method is being used for toughness measurements because the results can be used to evaluate the significance of defects by the fitness-for-purpose methods.

When CTOD specimens are notched at various locations in steel weldments, the toughness values exhibit a great deal of scatter. Careful examination of the most brittle specimens has revealed that certain microstructures that may occur in the heat affected zone (HAZ) are susceptible to brittle fracture. Based on these observations, detailed procedures have been developed to assess the fracture toughness of local regions within the HAZ. Using these procedures, it can be demonstrated that specific regions within the HAZ have consistently brittle behavior. These regions are called local brittle zones (LBZs).

Brittle fracture is a weak-link process that is triggered by a local cleavage event. Thus, LBZs constitute a risk that must be addressed by industry. The offshore industry has responded to this need by developing standards to assess the susceptibility of steels to the formation of LBZs, and by conducting numerous investigations into the nature, cause and significance of LBZs. To date, substantial progress has been made in understanding the metallurgical nature of LBZs and in measuring their fracture toughness. However, limited progress has been made in assessing the significance of LBZs on the structural performance of steel weldments.

A variety of test methods can be used to measure the toughness of steel weldments. These methods can be used to either detect the existence or assess the significance of LBZs. For quality control, several of the test methods can make important contributions.

The Charpy test is commonly used to evaluate the toughness of C-Mn steel weldments. For offshore structures, the United Kingdom Department of Energy (1985) has issued detailed procedures to evaluate HAZ toughness by Charpy testing. Specimens are notched perpendicular to the plate surface and parallel to the weld. All plates are notched within 3 mm of the face surface, and plates greater than 20 mm thick are also notched on the root side. Three Charpy tests are required at each of the three notch locations in the HAZ: at the fusion line, and at positions 2 mm and 5 mm from the fusion line. The Charpy tests are conducted at temperatures between -10 and -40°C depending on plate thickness, stress level, and post weld heat treatment.

A comparison of Charpy test results for HAZs in modern steels with high toughness and in older steels with lower toughness illustrates a key point (DeKoning, 1986). Modern steels have high toughness in the base plate and thus, the low toughness values in the HAZ are more noticeable in the modern steels than similar values in older steels, that is, LBZs are more apparent in higher quality steels than in marginal steels.

The Charpy test is not considered to be a reliable measure of a steel's sensitivity to LBZs. The main problem is sampling. When notched in the HAZ, the Charpy specimen tends to average the toughness of a variety of microstructures including the weld-metal, various regions within the HAZ, and the base metal. The averaging effect is compounded by, (1) the blunt notch which increases the volume of material exposed to the maximum normal stress, and by (2) measuring both the initiation and propagation energy of fracture. In addition to shortcomings in detecting LBZs, the Charpy test has limited value because the results provide only a qualitative measure of HAZ toughness, and thus, are not directly useful for fitness-for-purpose evaluations.

The CTOD test is a common method of measuring the fracture toughness of steel weldments. The preferred specimen is a full thickness, single edge notch bend specimen with a deep crack (crack length to depth ratio of 0.5) in a BX2B cross section. The idea is that the crack mouth opening is measured as load is applied, and fracture occurs when the CTOD determined from this opening reaches a critical value. Using the standard procedures of BS5762, this value is a material property for the specific specimen size, notch location and orientation, temperature and strain rate used in the test. By locating the crack tip in a specific region of the weldment (for example, the HAZ), the toughness of that region can be characterized.

In order to determine if a coarse grain region is an LBZ, the fracture toughness of the region can be measured by the CTOD method. Standard procedures have been developed to precrack fracture toughness specimens so that the crack tip samples the toughness of the coarse grain region. Because of the small size and irregular shape of this region, it is difficult to place the crack tip exactly. Special joint preparations are used to achieve a straight HAZ to facilitate placement of the crack tip. One edge of the joint preparation is straight and perpendicular to the plate surface, that is, a single bevel butt joint or a K-joint.

In the API (1987) procedures, the fracture toughness tests are conducted in accordance with BS5762 on test plates welded at three levels of heat input (the highest and lowest planned for production and 3 KJ/mm). The minimum toughness requirement is 0.25 mm (0.38 mm for thicknesses greater than 75 mm). After testing, the specimens are examined metallographically to determine if the crack-tip-placement requirements have been met. At least three specimens must have the crack tip in the coarse grained region of the HAZ (CGHAZ) for at least 15% of the specimen thickness. Two additional specimens are tested which have the crack tip in the Sub-Critical Region of the HAZ. These specimens are tested using the same procedures and minimum toughness requirements.

Pellini developed the drop weight NDT test to evaluate the ability of a steel to arrest a short brittle crack. He postulated that this type of capability would be required to protect a structure against the possibility that a local "hard spot" would crack and the elastic energy released would dynamically load the surrounding material, permitting cleavage propagation of the crack through the structure. This is similar to the situation that may arise due to LBZs. As such, the NDT test could be used to assess a steel's tolerance for LBZs.

NDT tests are conducted in accordance with ASTM Standard E208. A brittle weld is deposited along the mid-width of the tension surface of a simple beam specimen and notched at the center of the bead length. The specimen is impact loaded by a guided, free-falling weight. Deflection of the beam is limited by stops. The idea is that crack initiation occurs at the root of the notch in the weld bead and propagates across the specimen at temperatures below the NDT and arrests at the NDT and higher temperatures. NDT is defined as the lowest temperature at which the crack does not propagate to one or both specimen edges.

Recently, API (1986 a,b) has introduced optional NDT requirements into specifications for steel plates for offshore structures. For plate thickness of 16 mm and greater, two P-3 specimens (130 x 50 x 16 mm) must exhibit no-break performance at -35°C or lower.

LBZs are a problem for offshore structures in the North Sea. This has been the first offshore application for the CTOD method and it is by the CTOD method that LBZs are detected. The LBZs can be detected by Charpy tests, but the averaging effect of Charpy tests makes retests easier to pass. Also, with Charpy tests, if the LBZ problem persists, it can be solved by using better materials and welding procedures. Whereas with the CTOD test, low values are sometimes found even when the steel and welding procedures are satisfactory.

In the absence of failure experience, how can the significance of LBZs be assessed? Here, we consider the significance of LBZs in CTOD tests and in wide plate tests. These tests reveal the significance of LBZs under carefully controlled circumstances. If these circumstances also exist in the structure, the tests indicate the significance of LBZs in the structure.

A fundamental precept of fracture mechanics is that a small scale test can be used to measure fracture toughness, and the results can be used to predict the fracture resistance of a structure. Although this is

reasonably true for linear elastic and fully plastic fracture, the principle is simply not applicable to the fracture of structural steels in the ductile-to-brittle transition region. Here, the test results are strongly influenced by fracture mode (tearing or cleavage), which, in turn, is affected by strain rate, constraint, and departure. In a modern steel with a low inclusion content, the fracture toughness for ductile tearing is an order of magnitude greater than that of the same steel failing by brittle cleavage.

An LBZ is a site where cleavage can initiate in an otherwise ductile steel. Cleavage initiation releases elastic energy and causes a strain spike in the surrounding material. The dynamic loading can cause the surrounding material to fail by cleavage, and the cleavage can propagate through material that is resistant to cleavage initiation at lower strain rates. By changing the fracture mode to cleavage, an LBZ can cause a tenfold reduction in fracture toughness. Thus, LBZs are potential triggers for catastrophic brittle fracture.

In CTOD testing, the test conditions are designed to promote cleavage fracture. The preferred specimen design (BX2B, $a/W = 0.5$) maximizes constraint in the central 60 percent of the thickness. The test is conducted at or below the minimum service temperature. To reach specified minimum toughness levels, the uncracked ligament of the bend specimen is loaded beyond yield. These test conditions, coupled with carefully locating the crack tip in the CGHAZ, increase the possibility of cleavage initiation at an LBZ.

In structures comparable conditions of constraint, temperature, and load may exist at certain times in various locations. There is even the possibility that the tip of a critical-size crack in a CGHAZ will be in one of these places. It is precisely this possibility that is guarded against by ridding the structure of LBZs.

Testing full size structural elements overcomes the scaling problem encountered when applying fracture mechanics in the ductile-to-brittle transition region. If a cracked plate doesn't fracture until after gross section yielding, presumably the same crack size would not affect the performance of a similar plate in a structure—providing, of course, the loading modes are similar.

Wide plate tests are designed to simulate the most severe conditions of load, crack size and temperature likely to be encountered by a structure. However, the loading mode is usually tension, and the constraint depends on specimen design, the most severe constraint develops in double-edge-notched plates. Substantially less constraint exists for other through-crack configurations. The lowest constraint exists in surface notched plates because, here, the relaxation of constraint is controlled by specimen thickness instead of width.

For surface-cracked tension specimens, constraint is relaxed by through thickness yielding that occurs when the net section stress in the ligament exceeds yield (Chang and others, 1983). When the ligament yields, shear bands develop through the thickness, and the normal stresses at the crack tip are limited to the flow stress. Normal stresses under full constraint are nearly twice as high. If cleavage does not occur prior to ligament yielding, the CTOD rapidly increases with increasing load. Pictures of these blunted cracks in the CGHAZ (Denys and others 1986; Kozasa and others, 1987) provide a sense of assurance, but this surety is limited to surface cracks predominantly loaded in tension.

However, in a large study recently completed, five of the twenty wide plate tests failed at strain levels less than 0.5% (Webster and Walker, 1988). Thus, overall LBZ's can trigger brittle fracture in structural elements if the stress level and flaw size exceed critical values.

The selection of a method to measure fracture toughness depends on the purpose of the test. Several methods are recommended for quality control of the materials and welding practices used to build offshore structures.

Prior to procurement of the steel needed for an offshore structure, special welding and mechanical tests can be conducted to assure that the specific steels selected for the project have satisfactory weldability, including sufficient HAZ toughness. It is at this stage that the susceptibility of a steel to LBZs should be evaluated.

The CTOD test is recommended for detecting LBZs and for evaluating the susceptibility of a steel to the formation of LBZs. The procedures and requirements of API may be used.

During production of the steel, quality control tests are conducted to assure that the steel has satisfactory resistance to brittle fracture. It is at this stage that the steel's resistance to crack propagation

should be monitored to assure that it has sufficient tolerance for LBZs. Drop weight NDT tests are recommended to assure adequate tolerance for LBZs in the steels used for offshore structures. The NDT requirements of recent API specifications, mentioned above, may be used.

During fabrication of offshore structures, fracture tests on welds are conducted to qualify welding materials and procedures and to monitor the quality of production welds. At this stage, the toughness of the HAZ should be measured to assure that it exceeds the minimum toughness specified for the steel. The Charpy test is recommended to verify that the HAZ toughness exceeds the toughness specified for the steel. The Charpy requirements for the HAZ of recent UK DOE rules, mentioned above, may be used.

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Nitrogen Oxide Control Technology for Offshore Oil and Gas Operations

Principal Investigator: Lawrence Philp
Arthur D. Little, Inc.
5290 Overpass Road, Suite 227
Santa Barbara, California 93111

Objective: To assess nitrogen oxide control technologies applicable for offshore oil and gas operations and to recommend strategies for their development and demonstration offshore.

Nitrogen oxide (NO_x) has been shown to be a precursor to the photochemical formation of near-ground level ozone. Because of the intense usage of gas turbine- and diesel engines in Outer Continental Shelf (OCS) operations, NO_x has been an obstacle to the development of oil and gas off California. In particular, many of the areas in the vicinity of OCS developments are in non-attainment with the Federal standards for ambient ozone concentrations. These regions include areas around Los Angeles, Ventura, and Santa Barbara. Federal standards under the Clean Air Act consider an area to be in non-attainment with respect to ozone if, for more than 1 hour of a year, the ozone level exceeds 12 parts per 100 million (Environmental Protection Agency, 1987). In considering these regulations, state and local regulators as well as the public have developed serious concerns about OCS development activities over the potential for adverse impacts on air quality.

The development of advanced NO_x control technologies could reduce the significance of NO_x emissions as a barrier to OCS development. A large reduction of emissions would lessen the concern of regulators and the public alike.

The major sources of OCS NO_x emissions are:

- Production platform gas turbines,
- Crew boat and supply boat main engines (diesels) and,
- Exploratory drilling rig diesel engines.

Platform gas turbines are commonly used for electric power generation and as prime movers for major equipment, such as platform gas compressors. These units often use the waste heat in the turbine exhaust gas to heat a medium such as water (steam) or an organic heat transfer fluid. With waste heat recovery, the gas turbines are an energy efficient means of providing both useful thermal energy and shaft power for a variety of production platform purposes.

Water injection is presently used for NO_x emission control on platform gas turbines. Tests indicate that water injection at a ratio of 0.8 lb. water per pound fuel reduces NO_x emissions by about 70 to 75 percent from uncontrolled levels. Manufacturers guarantee approximately 60 percent NO_x emission reduction at full-rated load at this level of water injection.

Crew boats and supply boats are the most common means of transporting personnel and supplies from shore to platforms. These boats are usually based as closely as is practicable to the platforms serviced. NO_x emissions can vary depending upon the number of boat trips, the type of engines in the boats, and the location and number of platforms that are serviced. Typically, at least 80 percent of vessel NO_x emissions are produced while transiting (Santa Barbara Air Pollution Control District, 1987a).

Exploratory drilling rig diesel engines are one of the more significant sources of NO_x emissions associated with initial OCS development projects. A variety of types of exploratory rigs have been used in developing the Pacific OCS. Rigs used there have included *ser i*-submersibles, jackups, and drill ships.

Emission control technology is being applied to all categories of major OCS emission sources, including platform power generation, onshore stationary prime movers, and support vessels.

Gas turbines for power generation, cogeneration, and for prime movers have been one of the major sources of NO_x and other pollution emissions from OCS projects. Water or steam injection, which can reduce NO_x emissions by 50 to 70 percent, has been accepted as a standard control technology. In addition, an exhaust treatment scheme known as selective catalytic reduction (SCR) is being used for onshore

gas turbine generators. Units with both water injection and SCR have produced 90 percent less NO_x emission than uncontrolled turbines (General Electric, 1982).

Electrification of platforms can be accomplished in two ways. First, various prime movers such as those used to drill or operate cranes, could be replaced with electric motors which derive their energy from a single gas turbine generator unit installed on a platform. This modification could be readily accomplished. The alternative is to electrify the platform from shore, a costly procedure (Santa Barbara Air Pollution Control District, 1987b). A recently proposed modification to rate structures may help reduce the financial burden if enacted into law. In addition, shore-based cogeneration plants, which oil companies could build and operate for their own use and even for selling excess electricity to the public power grid, might prove to be economic.

With regard to exhaust gas treatment, a number of advances have been reported recently. One new technique which has received much favorable publicity is known as "Raprenox" and is discussed elsewhere in this report. See "Development of Raprenox for Diesel Emission Control," Robert A. Perry. In essence the inventor has developed a scheme which uses a common, nontoxic reagent, cyanuric acid, to treat the exhaust gases. The technique avoids the use of a catalyst or a hazardous reagent such as ammonia. Raprenox is in the early research stages and major questions, such as the mixing of the reagent and combustion temperatures for effective NO_x reduction, have to be answered.

Another example of exhaust treatment method is electrochemical reduction (Gordon, 1987). In this process, exhaust gas is passed through a solid state porous foam electrolyte made of stabilized zirconia. NO_x is reduced by an electrochemical reaction. This technology has also shown encouraging laboratory results.

Finally, improvements continue with exhaust treatment techniques which make use of novel catalyst formulations such as etched metal screens (Kittrel and Eldridge, 1985), Exxon's "De NO_x " (Lyon, 1987) and Fuel Tech's "NO_x Out" (Epperly and Broderick, 1988).

A number of control techniques have been demonstrated recently for crew and supply boats. In a recent field demonstration program, it was shown that turbocharging, injection timing retard, charge air cooling, and reduced boat speed can all contribute to a significant reduction in NO_x emissions. The combination of all four of these methods can reduce these emissions to below 50 percent of uncontrolled levels, with minimal impacts on other pollutant levels or on vessel operation.

Whereas, much progress has been achieved recently, there are new technologies on the horizon, which if made available to OCS activities, could further reduce air quality concerns. Technologies which show great initial promise include exhaust gas treatment, gas turbine combustion modification, diesel engine combustion modification, and alternative fuels.

Prior to adoption of advanced exhaust gas treatment for OCS activities, a number of issues must be addressed. Chief among them is the duty cycle of major OCS emission generating equipment. Many exhaust gas treatment technologies have been developed for steady, continuous sources, such as power station stack gases. The duty cycles of OCS equipment vary considerably, because of continual load fluctuations. Other issues related to exhaust gas treatment will also need to be addressed, particularly those regarding system reliability and any impacts on safety or operability.

Recent experimental effort in gas turbine combustors could also have a future role in OCS activities. NO_x emission levels as low as 10 ppm have been reported using dry low- NO_x combustors (Smith and others, 1986). Also, advances in catalytic combustors for gas turbines have been occurring (Makansi, 1988). Both of these techniques could significantly reduce NO_x emissions from turbines. As is the case with some other emerging techniques, the duty fluctuation cycles of offshore equipment pose a particular challenge for these schemes.

Improvements in emission levels of high speed diesel engines continue as manufacturers prepare for higher environmental pollution control standards. The engines which are being developed to meet these standards are of the same size as those which are found in crew boats and in a variety of construction equipment. Either these engines or some of the systems on these engines would be applicable for demonstration on OCS activities.

Alternative fuels have potential applicability for a number of OCS uses, including work boats and construction activities. Methanol has been demonstrated on engines of similar size to those found in

many OCS applications (California Energy Commission, 1986). Liquefied natural gas (LNG) is being used as a primary fuel on some work boats which are assisting in North Slope activities. Other alternative fuels with beneficial air quality implications include CNG, emulsions, and hydrogen fuel. Special proprietary additives could also be considered in this category. In general, all of these fuels may provide substantial benefits, but there are a number of issues to be addressed prior to their adoption, offshore safety being a primary concern. In addition, it should be recognized that some of the mobile equipment used for OCS activities is present in California waters only for short periods of time, and the cost and lead time required to modify the equipment to meet California standards may present difficult economic problems.

In the past, OCS projects have been able to draw upon emission control technologies which have been developed or demonstrated for other applications. In the future, control technologies for the OCS will, to some degree, have to be evaluated in the laboratory, possibly even before they are applied in other industries.

There are many unique aspects of OCS operations, and the structure of industry in general must be considered while technical improvements are being sought. Retrofitting of OCS facilities is greatly more complex than that required for comparably sized onshore facilities because of space and safety considerations. Further, the structure of the OCS industry must be understood, particularly in project phases, such as drilling and construction, where a significant fraction of the emissions is being generated by mobile equipment located in California only for short periods of time. The unique duty cycles of equipment for the various phases of OCS activities must also be considered. These duty cycles, as well as present emission levels, must be better quantified over time in order to match the performance capabilities of new control technologies to the emission characteristics of OCS sources.

Finally, as the search continues for more cost effective OCS controls, newly demonstrated technologies will play significant roles. In addition, there are some commercially available technologies which have not been used offshore, SCR for example. Due to technical, operational, and safety considerations, some of the more embryonic technologies may have promise for greater applicability.

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Response of Tension Piles to Vertical Seismic Motion in Saturated Fine Sand

Principal Investigator: Michael W. O'Neill, Ph.D.
University of Houston
Department of Civil Engineering
Houston, TX 77004

Objective: To investigate the geotechnical factors that can result in interface failure of piles in saturated, granular media when the piles are subjected simultaneously to biased tensile load and vertical seismic loading.

Plans for the increased use of compliant offshore structures envision the expanded application of piles loaded statically in tension. When such piles are placed in saturated granular soils in a geographic zone in which seismic activity can occur, the risk exists that the seismic action will produce a reduction of the capacities of such piles, possibly even resulting in failure during the seismic event. Research is therefore desirable to determine those conditions that would lead to reduced pile capacity in uplift.

Capacity reduction is believed to develop mainly because of the generation of excess pore water pressures in the near-field zone around the pile. This action, in turn, produces a reduction in the effective stress at the pile-soil interface, which reduces the frictional resistance available at the interface. The excess pore water pressure may develop from three potential sources. First, from the relative vertical shearing motion between the pile and soil, which may produce either positive (excess) or negative pore water pressures, and which is probably significant only at relatively large magnitudes of interface shear along the pile shaft; from the upward-propagating compression waves in the medium in which the pile is embedded, which may produce significant pore water pressures if the structure is near the epicenter of the event; and from the upward-propagating shear waves in the medium in which the pile is embedded.

The last factor is the effect most commonly associated with pore water pressure generation and liquefaction phenomena in earthquakes and has received significant attention in the past. The first two effects interact with one another, and they have not received much attention. This study therefore concentrates on the first two effects, while recognizing that the latter effect may also be important. In practical problems it may be possible to combine the latter effect and the effects specifically considered in this study using existing technology.

The problem is being studied experimentally, using small-scale modelling techniques, in which several key parameters are being varied. These parameters are:

- Relative density of the modelled deposit
- Magnitude of the mean ambient effective stress in the soil
- Signature of the seismic event
- Ratio of biased, static uplift load to static pile capacity in uplift
- Condition of the interface.

A pressure chamber is used to contain the saturated soil deposit and to simulate effective stresses and drainage conditions, as shown schematically in Figure 1. Drainage is permitted only at the top of the chamber during a simulated seismic event. After the chamber is saturated and pressurized to simulate a prescribed effective stress condition, the test pile is driven, or driven and grouted, into the simulated deposit, which consists of a fine, siliceous sand that is initially installed by fluviation (relative density = 45%) or pluviation (relative density = 85%). The installation process is allowed to influence the relative density and state of stress within the soil in the vicinity of the pile and the adhesion properties at the pile-soil interface in a manner similar to that which may occur in the field. A biased tension load determined from a prescribed ratio of static uplift capacity is then applied and maintained during a test, and the chamber is excited through its base by a servo-controlled testing machine.

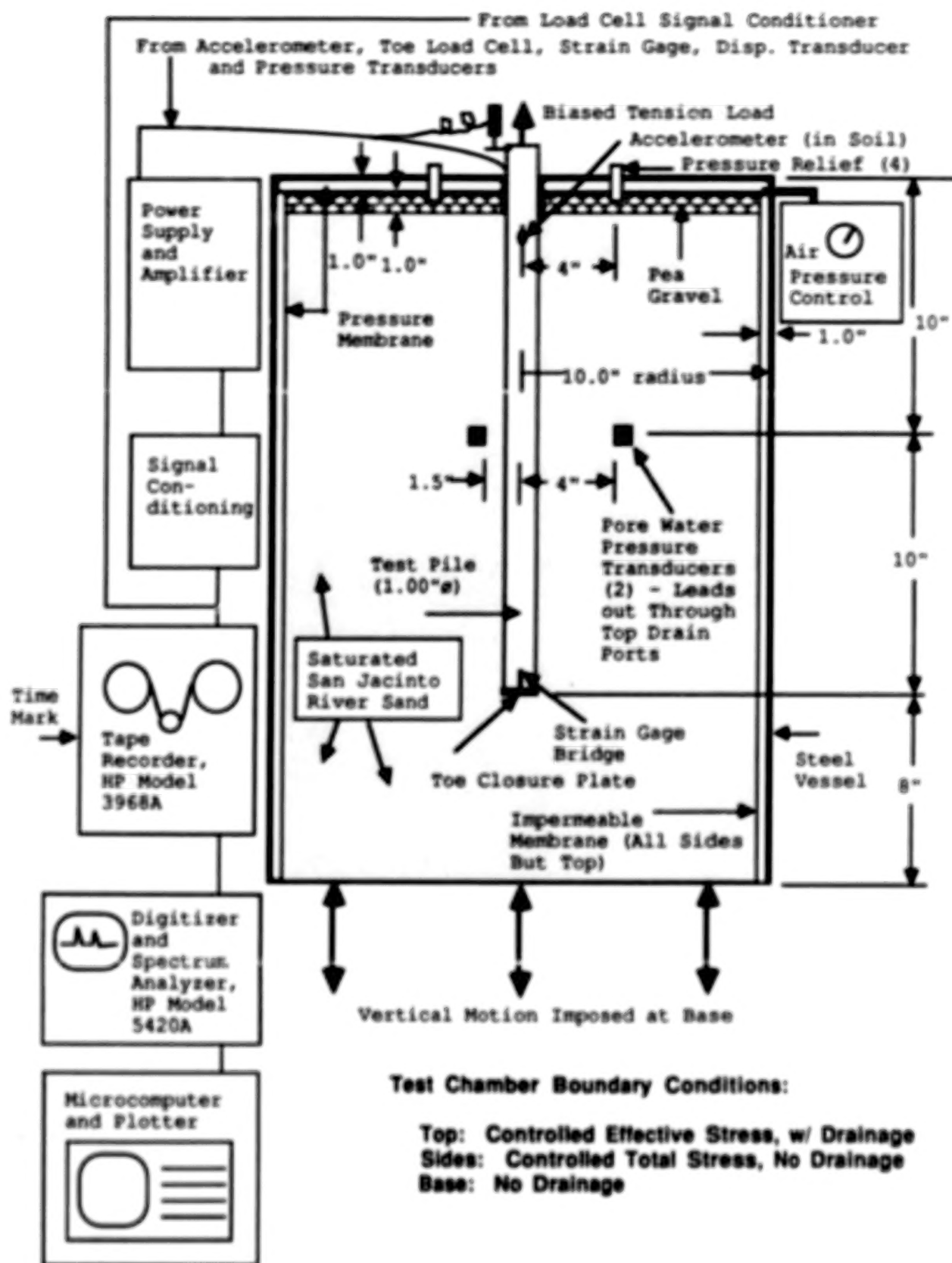


Figure 1 — Pressure Chamber and Instrumentation.

A feedback accelerometer in the chamber is acquired during testing by a controller that signals the machine to simulate a programmed seismic event. Pore water pressures are monitored during the simulated event, as is the deformation of the head of the pile and the load distribution in the pile. Once the simulated event is completed, the pile is subjected to a quasi-static uplift test to failure to ascertain whether the seismic motion has produced any residual capacity loss, if the pile has not failed by pullout in the simulated seismic test. Such loss would not be due directly to excess pore water pressure at the pile-soil interface, which will have dissipated by the time of this test, but may develop due to the motion of the soil particles during vibration, which may cause mass contraction of the soil and reduce the horizontal effective stress at the pile-soil interface. Load distribution and pore water pressure records are examined following a test to determine the source of failure, if any.

The test pile is a 1-in.-diameter by 20-in.-long, closed-toed aluminum tube, and the relative pile-soil stiffness in the chamber approximates that found in typical offshore piles. The vertical components of two separate seismic records are being modelled. One is a record that was measured on the seafloor off Southern California in July, 1986, (Richter magnitude 6 event) and the other is an amplified version of the same record, which is being studied to represent the effects of a much stronger event.

Conclusion

The study is expected to define the ratio of uplift bias load to static uplift capacity that can be tolerated in tension piles in medium to dense sands under the vertical components of moderate and strong earthquake loading. The effects of depth of the pile and preconsolidation characteristics of the sand will be observed through the influence of the magnitude of effective chamber pressure on the deposit. Through independent means or through additional research, further increases in pore water pressure due to the effects of vertically propagating shear waves can be combined with the results of this study to evaluate the capacity of tension piles under more complex loading states.

Soil/Pile Interaction Due to Seismic Response of Subsea Soils

Principal Investigator: Toyoaki Nogami
Scripps Institution of Oceanography
University of California San Diego
La Jolla, California 92093

Objective: To investigate offshore-environment effects on seismic response of seafloor and pile foundations.

One of the most difficult factors to be considered in designing fixed offshore platforms in active seismic areas is seismic loading effects on the seafloor soil and the resulting foundation behavior. In offshore environments, the soil is completely submerged and can be located at some depth below the water surface. These environments affect the seismic response of the soils and foundations offshore and their effects must be carefully taken into account in the seismic response analysis of fixed offshore structures. However, land-based approaches and records are often used in the evaluation of the seismic response behavior of foundations of offshore structures, without considering these environment effects properly. The ultimate objective of this study is to develop the seismic response analysis method of pile foundations of offshore platforms while properly considering the offshore-environment effects. As the first step towards this objective, the project investigates how the offshore environment affects the seismic response of seafloor and pile foundations. The research is being conducted in cooperation among three teams, including the Sandia National Laboratory, a group of Japanese universities and the Scripps Institution of Oceanography. The Japanese team has set up instrumentations at a piled platform located offshore Japan in order to obtain seismic response records. Figures 1 and 2 show the location of the platform and arrangement of instrumentations, respectively. The Sandia National Laboratory has set

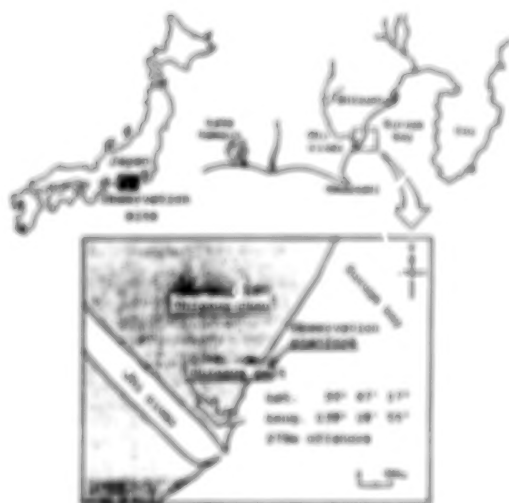


Figure 1 — Location of Observation Piled Platform Offshore Japan.

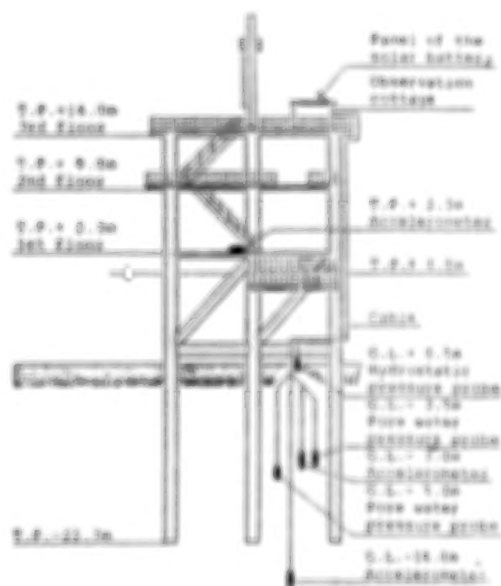


Figure 2 — Arrangement of Instrumentation at Offshore Japan Platform.

up instrumentation at a site located offshore California under a Minerals Management Service sponsored research project entitled "Seafloor Seismic Data Study".

Soils provide input motions to pile shafts through free-field ground motions and provide soil-pile interaction forces. The effects of the offshore environment will be investigated for the soil and regions covered in the project.

The offshore-environment effects result from the coupling between the soil skeleton and fluid in and above the seafloor. Two different types of soil-fluid couplings exist. They are: (1) elastic coupling through an elastic volumetric strain of the solid mass and (2) anelastic coupling through a permanent volumetric strain of the soil mass primarily induced by the shear. The first type of coupling is associated with the P-waves and Raleigh waves, whereas the second type of coupling is associated with S-waves. The second type of coupling results in a soil liquefaction and has been investigated extensively in the past. However, the first type coupling effects on Raleigh waves behavior have been studied very little. Figure 3 shows seismic response analysis results obtained for an offshore gravity base structure and free-field ground response at the surface. Significant structure responses occur at not only the period of large ground accelerations but also the period of small ground accelerations where Raleigh waves are predominant. This is because Raleigh waves have long periods and can excite structures with a long natural period significantly. Therefore, the offshore environments may strongly affect the seismic response of piled offshore platforms through Raleigh waves.

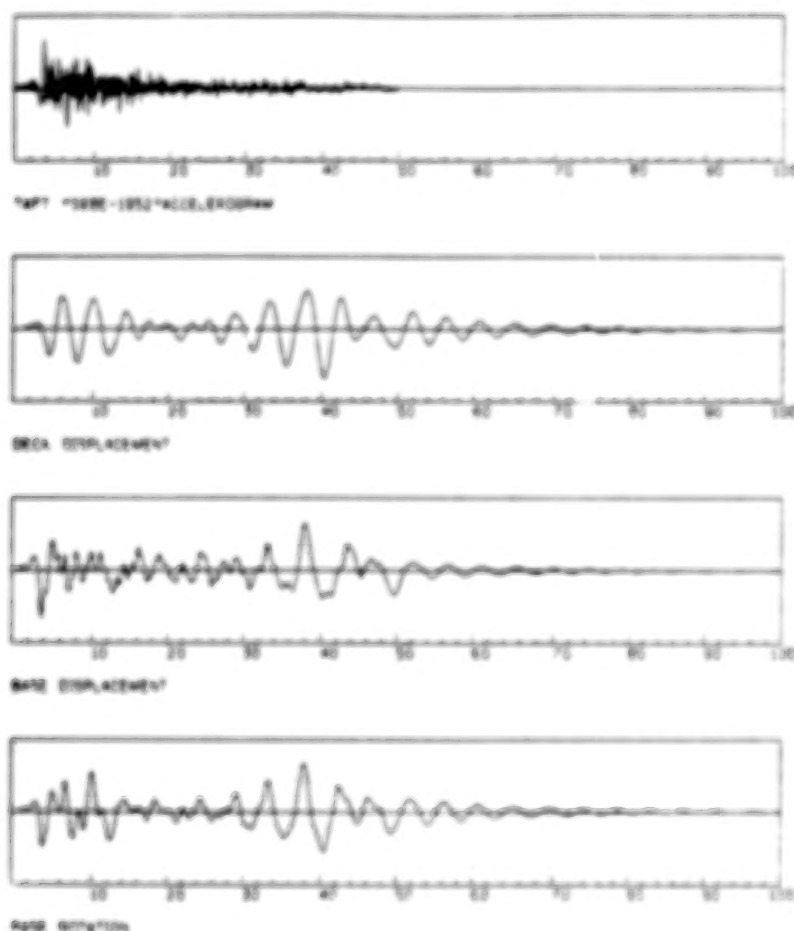


Figure 3 — Computed Seismic Responses of Gravity Base Offshore Platform and Free-Field Ground Motion.

Because of a potentially significant role of Raleigh waves in seismic response to offshore platforms, a part of the research will be conducted mainly on Raleigh wave motions. First, the analysis tool for numerical evaluation of Raleigh wave behavior in the seafloor will be developed under elastic conditions. This is necessary because the principal mechanism of offshore-environment effects on Raleigh wave motion does not depend on the anelastic soil behavior and the elastic conditions will be sufficient to examine these effects. Using Biot's equation for the dynamic response of a fluid-saturated elastic porous medium, formulations based on either a transfer matrix method or finite element method will be developed for the evaluation of Raleigh wave motion in a fluid-saturated porous medium. The transfer matrix approach was originally used by Haskell (1953) for the analysis of elastic solid response to incident body waves. This approach was further extended for the computation of a fluid-saturated elastoporous medium response to incident body waves (Yamamoto, 1983). The finite element method was developed and used for the studies of the soil response to Raleigh waves (Lysmer, 1970). The soil medium was assumed to be a visco-elastic medium in this finite element method. The finite element method was also formulated for a fluid-saturated porous medium and used in the dynamic problems (Zinkiewicz et al., 1984; Ghaboussi et al., 1972; Prevost, 1982). However, those formulated for a fluid-saturated porous medium appear not yet to have been used for the evaluation of Raleigh wave motion in a fluid-saturated porous medium. After the development of the analysis tool either based on a transfer matrix method or finite element method, parametric studies will be conducted to study the effects of the water both above and inside the soil deposits on Raleigh wave motions. Various cases will be considered for water depth above the soil deposits, porosity of the soil, and elastic moduli of the soil skeleton.

The aforementioned second type soil-fluid coupling can cause a development of the residual porewater pressure in the soil mass, resulting in changing the soil-pile interaction characteristics. This behavior will be investigated in this part of the study. The finite element program will be developed to investigate the seismic response behavior of soil-pile systems. Formulations in the program will be based on Biot's equation of the dynamic response of a fluid-saturated porous medium. Anelastic behavior of the soil skeleton will be considered through the soil stress-strain constitutive relationship proposed by Hirai and Satake (1984).

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Interference Problems Associated With Risers in Floating Production Platforms

Principal Investigator: F. Rajabi, PhD.
Marine Engineering Division
Brown & Root U.S.A., Inc.
Houston, Texas 77001

Objective: To assess riser interference/clearance problem in a tension leg platform-based floating production system (TLP-FPS) and a semisubmersible-based floating production system (SEMI-FPS).

As the search for energy moves into progressively deeper water, floating production systems (FPS) such as tension leg platform-based FPS (TLP-FPS), semisubmersible-based FPS (SEMI-FPS) and monohull FPS (Mono-FPS) become increasingly attractive concepts for offshore operators.

Risers are critical and delicate components of an offshore FPS and connect the surface facilities to the subsea equipment while suspended beneath the FPS. Economic and operational considerations may dictate that drilling production, and transfer of production occur simultaneously through various closely spaced riser types. Several riser arrangements can be considered including individual riser arrangement, riser bundles, or hybrid systems consisting of rigid and flexible risers. Regardless of the FPS deployed and the riser system configuration used, at any time an array of risers having distinctly different physical properties and tension requirements are bound to work simultaneously. Relative motion among various components of an FPS may cause interference between risers, between risers and platform or between risers and mooring lines. Therefore, this problem is of paramount importance in the design and operation of floating platforms.

To reduce the floating production platform size and cost, the usual approach is to minimize the space between risers and structure. However, this spacing cannot be specified arbitrarily and special considerations must be given to this problem.

To avert riser interference, the temptation is to increase the riser top tension. It is important to note that the spacing between risers, risers and hull, or risers and mooring system are very important and the risers top tension cannot be changed arbitrarily without causing new problems. A wide riser spacing will result in a large fire-restricted platform area. Furthermore, it may impose restrictions on hull design such as not permitting any primary bracing members in a large central area of the platform structure. The riser top tension is a weight burden as far as the FPS is concerned and top tension cannot be increased indiscriminately without careful consideration. Another important factor, which must be considered, is the effect of water depth on spacing requirements.

Therefore the objective of this project is a critical study of the interference problem involving risers, production platform structure and mooring system.

A strategy for this study considers the following interference scenarios: 1) in-place riser-to-riser interference problem; 2) in-place riser-to-hull clearance problem; 3) in-place riser-to-mooring system interference problem; 4) riser installation and retrieval clearance problems with other risers, hull, and mooring system.

In-place riser-to-riser interference is a potential problem in FPS where individual risers connect wellheads to the production platform. Figure 1 shows schematically interference of two adjacent risers in a TLP. This problem is typical of the situations in which economic and operational considerations may dictate that drilling, production, and transfer of produced fluids occur simultaneously. This results in an array of risers having distinctly different physical properties, tension settings, and internal fluids. The motion of these risers, caused by waves, current, and platform motion, may be out of phase with each other or with the platform. If the spacing is not adequate, they may come in contact with each other with unpredictable consequences. There are two remedies for this problem; increase of top tension settings or enlarge the well spacing.

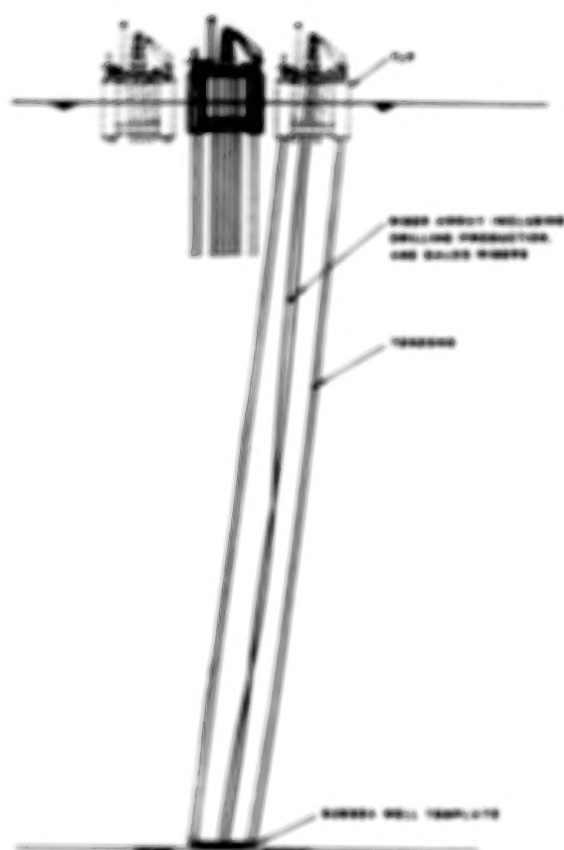


Figure 1 — Riser-to-Riser Interference Problem.

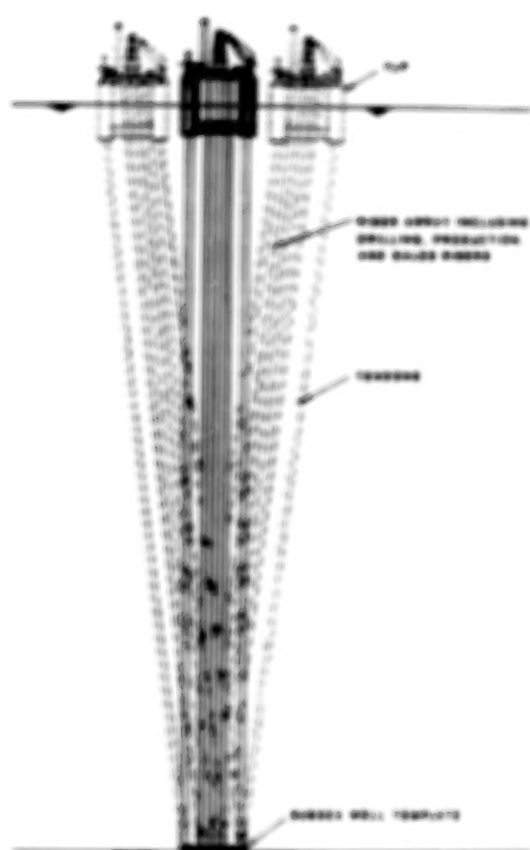


Figure 2 — Riser-to-Hull Interference Problem.

FPS's are very sensitive to weight increases and riser tensions configure as weight burdens for these structures. Therefore, increasing riser tensions will reduce variable deck load carrying capacity of FPS and will require larger displacement and cost.

Some FPS's, especially converted drilling semisubmersibles, include primary bracing members in the central area of the platform substructure. These bracings are potential contact points for risers as the platform moves to its extreme offset positions and risers oscillate under action of waves and platform motion. Contacts may inflict permanent damage to the riser pipe or cause the riser string to buckle, puncture or break.

Flexible production risers are used in some production arrangements and may come into contact with FPS hull or structural bracing. Figure 2 shows schematically the clearance problem between riser and hull in a TLP-FPS.

Flexible production risers are becoming very attractive in marginal field development. Some new FPS concepts propose to use flexible risers as the main conduits for production transfers. The flexible risers present many operational and cost saving advantages. However, the flexibility of these risers makes them susceptible to undergo large oscillations. These oscillations, combined with catenary configuration of the riser and large offsets suffered by an FPS, may create situations in which interference with mooring systems can occur. Figure 3 shows schematically the potential interference of a flexible riser and a TLP tendon system. This contact may not be detrimental to the mooring system; however it may be detrimental to the flexible user.

This problem cannot be easily corrected since flexible risers, by design, are not tensioned and they hang under their own weight and take a catenary configuration. Therefore, control of interference by adjusting top tension is not possible.

Interference of risers and the mooring system is less probable if rigid risers with high values of top

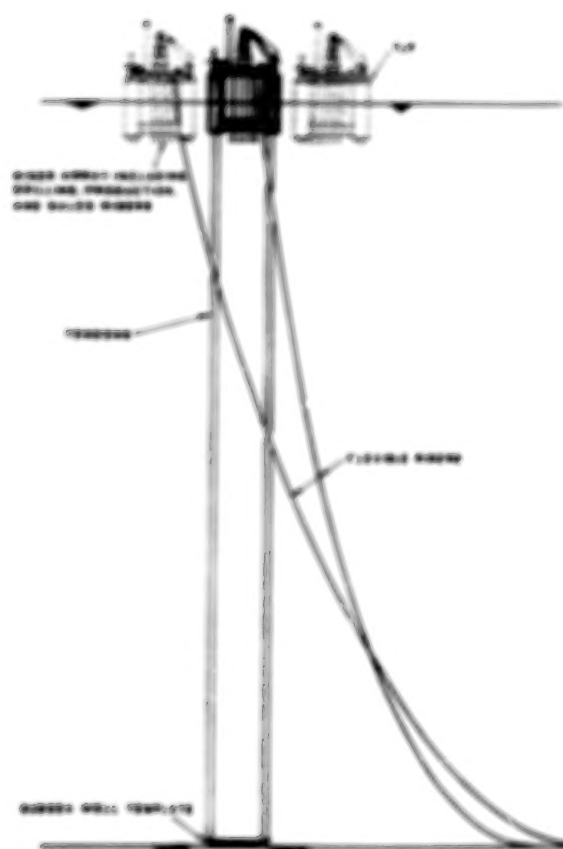


Figure 3 — Riser-to-Mooring System Interference Problem.

tension settings are used. However, in this case the interference becomes of great concern during installation and retrieval operations, especially in situations where a BOP stack is deployed.

One of the most critical times when riser-to-riser interference, riser-to-hull contact, or riser-to-mooring system interference can occur is when risers are being run or retrieved. When a current is present, it causes the FPS to move down-current from the template. With the FPS in this position, a riser being run without guidelines would trail off down-current even more than the platform and would likely contact any downstream risers. Using a guideline system to run the risers will help minimize the possibility of interference.

Whether interference occurs will depend on the severity of the environmental conditions, the tension in the guidelines, and the configuration of the risers, along with the weight and size of any equipment at the base of the riser.

Conclusion

This project involves a critical study of the interference problem considering risers, production platform structure and mooring system. The study will be carried out in two distinct phases. Phase 1 will be concerned with a survey of various FPS's, identification of the riser clearance/interference problem and the specification of the systems to be analyzed in detail in Phase 2 of the study.

In Phase 2, the systems specified in Phase 1 will be analyzed to develop a critical assessment of the interference/clearance problem. Basically, this study will address the potential of each system to be involved in an interference/clearance situation which may result in a catastrophe. This study will also reveal the kind of interference/clearance problems which should be absolutely avoided and what type of interference/clearance conditions can be accepted if necessary precautions are taken.

Structural Systems Reliability

Principal Investigator: C. Allin Cornell
Dept. of Civil Engineering
Stanford University
Stanford, CA 94305

Objective: Assess and develop methods to calculate the reliability of offshore structural systems.

A joint industry/government study was initiated to conduct a critical review of the status of structural systems reliability, to evaluate its potential utility to the offshore field, and to develop improvements and new research directions as needed. Structural systems reliability is associated with quantification of notions such as redundancy, robustness, and inspection-repair strategy.

The interest in assessing the reliability of systems, as distinct from structural components, is a natural extension of the current broad use of probabilistic descriptions of the offshore loading environment (waves, wind, current, ice, etc.) and the growing application of probability-based offshore structural codes for member-level design, for example, the NPD code and the draft API-2A LRFD code. Structural systems reliability research has a relatively long history (e.g., Freudenthal, A.M., et al., 1966; Cornell, 1967) but recent interest has been extremely strong. The apparent reasons for this intense activity are (1) the field's success in research and practice with member-level reliability, (2) the rapid decrease in computational costs, and (3) the development of the first-order reliability method, FORM (e.g., Rackwitz and Fiessler, 1977) that permits rapid, efficient estimation of (small) probabilities of unions ("or's") and intersections ("and's") of events related to functions of large numbers of arbitrarily distributed random variables. The FORM capability permits one to calculate such failure-sequence probabilities as keep the event: the (random) capacity of member 1 being less than the force induced by the (random) applied loads and member 2's capacity being less than the force induced by the loads when the structure has been altered by the failure of member 1, or member 2 fails in the intact structure and member 1 fails in the so-altered structure, etc. Clearly these are the kinds of complex events and relationships one encounters when dealing with multi-member, statically indeterminate structural systems such as those found in typical offshore steel jacket structures.

The first phase of the project focused on (1) the review, categorization, and critique of the many contending methods found in the literature (Karamchandani, 1987); (2) the assessment of the needs the industry has for systems reliability capabilities; and (3) presentation of the concepts and elements of structural systems reliability (Cornell, 1987). The second phase turned to developments to improve the mechanical and other modeling limitations in the more cost-effective (but special purpose) systems reliability methods found in the literature, and to exploration of methods capable of treating more general problems.

To demonstrate both structural systems analysis' capabilities and its potential benefits with respect to resolution of industry issues, the project team conducted a major study (Nordal, et al., 1987; Nordal, et al., 1988) of an eight-leg steel jacket production platform designed and studied deterministically by others (Lloyd and Clawson, 1987). The layout of the structure is shown in Figure 1; a typical failure tree developed for the study by the program FAILUR is shown in Figure 2.

A failure tree displays graphically alternative member failure sequences and the calculated reliability indices for sets of branches (failure paths). (The reliability index β is monotonically related to the probability of occurrence, smaller β values imply more likely failure sequences.) This tree shows, for example, that member 140 is the most likely to be overstressed in the intact structure, and member 144 is most likely to follow it; these are two diagonal braces in the upper part of the structure. By analyzing the unions of these several more likely paths, it was concluded that the system β is approximately 3.03 (a failure probability of about 1×10^{-9}).

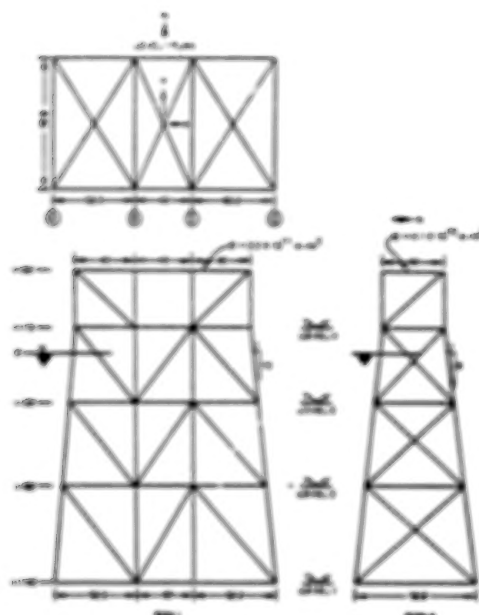


Figure 1 — Example Structure (Lloyd and Clawson, 1983).

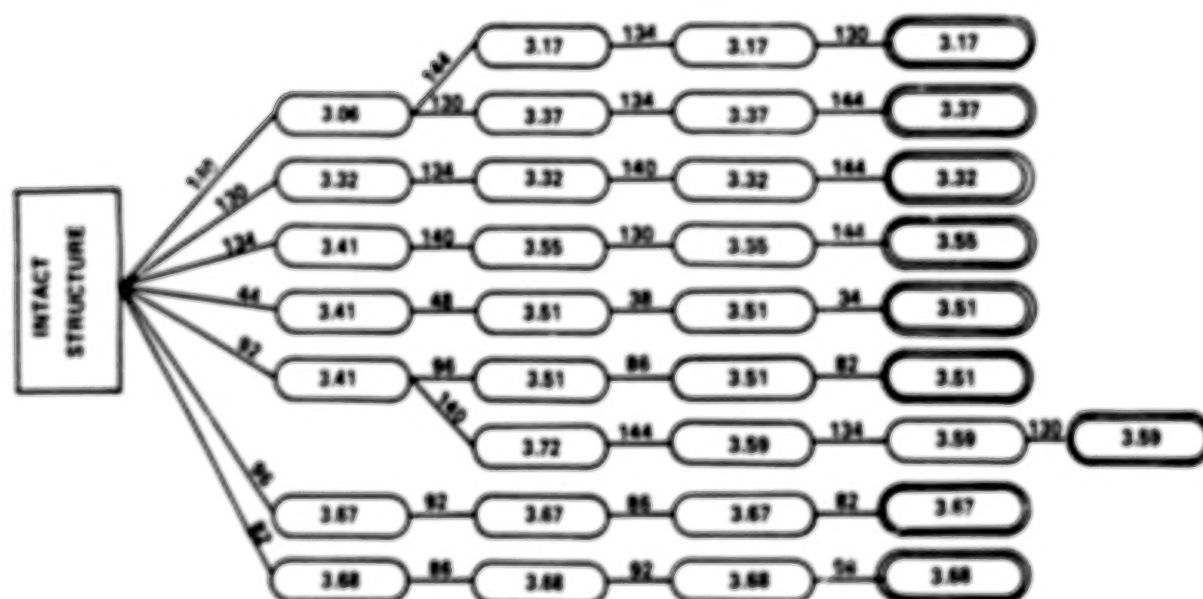


Figure 2 — Failure Tree, Showing Member Numbers and Reliability Indices of Partial Paths.

The study compared this structure's reliability and redundancy both in an X-braced configuration and in a modified, K-braced form. Redundancy is measured in this project by the *conditional* probability of total system failure *given* that any member has failed. (A statically determinate structure therefore has a redundancy measure of one.) This X-braced system had a redundancy measure of 0.1; the K-braced system redundancy measure was less good, 0.7.

Subsequent studies on this same structure have considered the reliability given a damaged member (robustness), the safety implications of wave forces at the deck level, and the degree of rigor in the representation of the post-buckling behavior of the (critical) compressive braces (Cornell, 1988). In short, the project has attempted to demonstrate how systems reliability can bring new information to bear on problems already identified as being of industry concern.

Subsequent project reports will present a set of specifications for a currently feasible, next generation structural systems reliability analysis program for jacket-like structures, and will address techniques for efficiently estimating the reliability of more generally formulated structural systems problems, including time-varying loads and responses.

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Evaluation of the Spray Ice Barrier at the CIDS Antares Site During 1985, Using Time-Lapse Photography

Principal Investigator: William St. Lawrence
Polar Alpine Inc.
1442A Walnut St., #236
Berkeley, CA 94709

Objective: To evaluate the behavior of the spray ice barrier constructed around Global Marine's Concrete Island Drilling Structure (CIDS).

During November 1984 a spray ice barrier was constructed by EXXON Company U.S.A. around three sides of Global Marine Drilling Company's Concrete Island Drilling Structure (CIDS) (Jahns and Petrie, 1986). As one means of monitoring the effectiveness of the structure, EXXON Production Research Company deployed six time-lapse cameras around the CIDS. The cameras were at the CIDS Antares location from mid-January through mid-August, when the CIDS was moved from the Antares location.

The six cameras were initially located on the spray ice barrier. Each camera was set up so that it could record sea ice movements and how the movements affected the spray ice barrier. The cameras remained at their locations on the spray ice barrier until early June.

With the approach of breakup in June, the cameras were removed from the barrier and redeployed on the CIDS itself. With the relocation of the cameras, the emphasis changed from monitoring the manner in which the barrier protected the CIDS to how the barrier reacted during the open water season. The cameras were left in place on the CIDS until it was moved in mid-August.

The cameras used for the monitoring of the CIDS barrier were two 16mm Bolex, H16EL cameras and four Automax Model GS-2 cine/pulse cameras. The different format cameras were selected primarily for their operating characteristics, especially their ability to operate under the harsh conditions of Arctic winters. To insure that the cameras operated properly, each camera was enclosed in a specially designed heated enclosure.

During the course of the monitoring program, 12,800 feet of 35mm film and 6,400 feet of 16mm film were exposed. The interval between frames ranged from eight minutes for the 35mm film to one minute for the 16mm cameras. A total of 204,800 individual 35mm images and 256,000 16mm images were recorded for analysis. To reduce the large amount of film to manageable form, the developed film was transferred to a one-inch video master tape and simultaneously to one-half-inch VHS format tapes. The one-inch master video tape is used as the primary storage medium. The one-half-inch tapes are used to carry out the photogrammetric analysis.

The spray ice barrier was constructed during the closing months of 1984. The time-lapse cameras were not deployed until January 25, 1985. Thus information on ice conditions from the formation of the barrier through January were not recorded. At the time the cameras were installed, there were ice pile-ups against the spray ice barrier on the northwest side of the CIDS and also on the eastern side. Through the winter monitoring period from January to May, no ice movements detectable to the cameras were recorded. It is possible that some low amplitude (one- to five-meter) ice movements took place during this period that could not be detected by photogrammetric analysis using the equipment available.

At the end of May and into June, changes started to take place in the ice surrounding the spray barrier. These changes consisted of the formation of melt ponds on the ice surface and a noticeable change in the texture of the ice. On June 8, 1985, the cameras were moved from their locations on the spray barrier to positions on the CIDS to record the breakup of the sea ice, and the dissolution of the barrier.

During the summer monitoring period a great deal of ice activity took place around the CIDS. The breakup of the sea ice took place, and the spray ice barrier underwent significant melting and intermittent periods when large blocks calved from the barrier. By the time the CIDS was moved from the Antares

location on August 17, 1985, a large portion of the barrier had been removed. A detailed analysis and chronology of the sea ice breakup around CIDS and the manner and timing of the breakup of the spray ice barrier was conducted. A narrative videotape was made to illustrate the nature of the breakup of both the sea ice and the barrier.

This work was carried out in cooperation with the Cold Regions Research and Engineering Laboratory, EXXON Production Research Company and the Minerals Management Service. EXXON Production Research Company provided the data for analysis. The Minerals Management Service provided funding for the analysis of the data. Due to the contractual arrangement under which this work was carried out, specific information generated from this program will remain confidential through the end of December 1991.

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Helicopter-Borne Laser Ignition of Oil Spills

Principal Investigator: Michael Frish
Physical Sciences Inc.
Research Park, PO Box 3100
Andover, MA

Objective: To experimentally verify the optical design of a system for using airborne lasers to ignite Arctic oil spills.

In the event of an Arctic oil spill, either from a shipwreck or offshore oil well blowout, it is envisioned that oil reaching the surface of an ice field melting during springtime will form tens of thousands of pools, each having typical dimensions of a few tens of meters (Lewis, 1976). The technique of choice for removing these pools before they transform into unremovable tar is to set each afire within a few days of its appearance. Due to the remote location of a potential accident, ignition of oil must be accomplished from an airborne vehicle. To date, only pyrotechnic ignitors have been able to achieve this task (Ross, 1984). Unfortunately, these devices have shelf lives of only about five years, and production of sufficient stock to clean up one major spill could require a recurrent cost of several million dollars. The logistics of manufacturing and transporting the thousands of devices to a spill site have yet to be addressed.

During the past four years, a novel dual-laser approach to starting oil pool fires has been developed. After initial theoretical and laboratory studies (Frish and others, 1985a, and 1987), a ground demonstration of the technique was performed outdoors in conditions simulating an Arctic environment (Frish and others, 1985b). Following that success, a helicopter deployable system was designed (Kung and others, 1986). Testing of certain critical aspects of the optical components within that design is currently underway.

The laser ignition process may be summarized as follows: A continuous-wave (CW) carbon dioxide laser is used to heat a portion of the surface of an oil pool to its flashpoint temperature and simultaneously establish a thermal field within the oil which will support the growth of a nascent flame. A focused, pulsed laser beam then provides energy which creates a momentary "spark" above the oil surface to ignite a fire. The technical advances that led to the success of the technique were: (1) learning the requirements to start a small diffusion flame which is able to sustain itself and spread over a large pool of cold oil, and (2) determining how to satisfy these requirements using lasers.

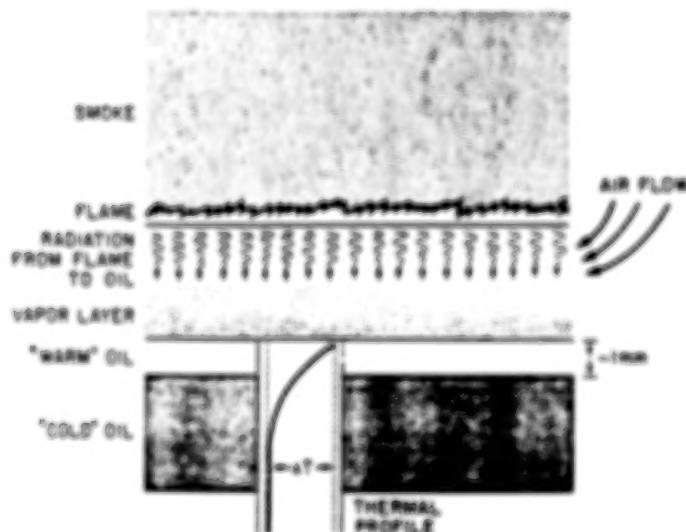


Figure 1 — Salient Features of a One-Dimensional Diffusion Flame.

A schematic illustration of a one-dimensional diffusion flame is presented in Figure 1. At the surface of the cold liquid is a relatively hot layer from which fuel evaporates and mixes with the air above. Combustion occurs in a very narrow layer located a small distance above the surface of the fuel, and combustion products such as hot soot and gases rise above this zone. As the fire burns, combustion energy is radiated and conducted through the air back to the oil pool, thus providing the power required to continue vaporization of new fuel and sustain the burning. If this power is insufficient to overcome the heat flux transported to the bulk liquid by conduction and convection, the surface cools to a temperature below that at which sufficient vapor is produced (below the flashpoint) and the fire extinguishes itself. Thus, the liquid will burn only after several criteria are satisfied: 1) The surface of the liquid must be hot enough to provide a vapor above the surface which, when mixed with ambient air, is combustible; 2) This vapor/air mixture must be raised briefly to a temperature sufficiently high to initiate combustion; and 3) The liquid fuel must establish temperature and flow fields which transport less power into the liquid's volume than a nascent flame is capable of supplying back to the liquid surface.

Cold, aged crude oils fail to inherently satisfy any of these criteria. To generate a combustible vapor mixture, the surface of the liquid must be heated to its flashpoint temperature, typically as high as 100 C. To ignite the vapor mixture, it must be exposed to a heat source of 700 C or more. The third criterion requires that the liquid absorb a certain amount of energy before the fire is ignited.

Laser beams, which act as remote infrared energy sources, are used to satisfy each of these requirements in the Laser Ignition of Oil Spills (LIOS) technique. By selecting appropriate combinations of laser power, intensity (power/unit area), and irradiation time, ignition of sustained, spreading fires on the surfaces of cold, aged oil pools is accomplished. The powers and intensities delivered by the laser beams are controlled by the choice of lasers and the use of focusing or defocusing optical components. Two lasers are used in tandem as illustrated by Figure 2: A moderate power (< 1000 W) CW laser continuously irradiates or "preheats" a small portion of the oil surface thereby establishing the thermal and flow fields required for vapor production and flame survival, satisfying criteria 1 and 3. Concurrently a high power (7 MW) short-pulsed (2 ms duration) focused laser fires once per second. By focusing this pulsed laser beam to provide a fluence (energy/unit area) exceeding 10 J/cm² at the surface of the pool, its energy is absorbed in the vapor above the oil thereby generating temperatures high enough to initiate the combustion reaction, satisfying criterion 2. When conditions are right, the vapor mixture ignites and initiates a self-sustaining fire. Carbon-dioxide (CO₂) lasers have been used exclusively in this technique because of their advanced state of development, energy conversion efficiency, availability and cost. These lasers radiate at a wavelength of 10.6 mm, in the far-infrared.

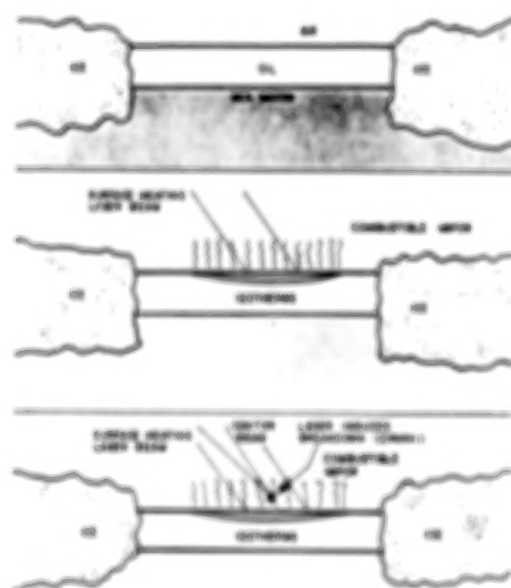


Figure 2 — Laser Ignition of Oil Spills Concept and Sequence.

The helicopter-deployable version of the LIOS system has been designed with the following features:

1. Can be installed in a Sikorsky S61 or comparable helicopter without affecting airworthiness or safety;
2. Incorporates a CW CO_2 laser producing up to 1000 W of power and irradiates the oil pool with the required preheating intensity of $5\text{--}10\text{ W/cm}^2$;
3. Incorporates a pulsed laser which is focused to provide sufficient fluence to ignite, from a distance, fires on preheated oil pools;
4. Holds the laser beams on target despite helicopter movements and vibrations;
5. Provides sufficient power and cooling capability to operate all of the system components; and
6. Can be operated by an aircraft maintenance technician.

Assuring that the pulsed laser beam is focused at the surface of the oil pool to a fluence which is sufficient to ignite the preheated oil is critical to the success of the system – no spark, no fire. As already mentioned, the fluence per pulse should exceed 10 J/cm^2 at the oil pool surface. Throughout the experimental development process, this fluence was achieved by focusing the pulsed laser beam with short-focal-length mirrors located within one or two meters of the oil surface. It had not been shown, except by calculation, that sufficient fluence could be provided from a hovering helicopter.

This uncertainty has now been resolved – a focusing system which meets the mission requirements has been constructed and tested. In addition to meeting the minimum fluence requirement, the optical system design satisfies certain economic constraints as well as limitations imposed by the CW laser which force the system to operate from a helicopter hovering at a fixed altitude of about 20 m above ground level. Individual oil pools are to be selected by pointing the lasers over elevation angles between 0 and 49 degrees, corresponding to slant ranges between 20 and 30 m as illustrated in Figure 3. Therefore the pulsed laser focusing system incorporates a capability to alter its effective focal length through these ranges. Furthermore, a means for the operator or automatic controller to determine when the laser is properly focused is included.



Figure 3 — Operational Scenario for Airborne LIOS System. Not to Scale. (After Reference 6).

The pulsed laser currently used as the igniter is a Lamontics Model TEA-103 operated in an unstable resonator optical configuration. This laser is nominally capable of yielding 8 J of focusable energy per pulse. To provide a fluence well in excess of the requisite 10 J/cm^2 at the oil surface, the beam is focused to a diameter of about 0.4 cm using a two-element Cassegrainian telescope as illustrated in Figure 4. The laser beam is first expanded by a -35 cm focal length, 2.5 cm diameter concave lens, and then focused by an 80 cm focal length, 25 cm diameter concave mirror. The two elements are nominally separated by 185 cm. The distance from the concave mirror at which the beam achieves its minimum diameter is the effective telescope focal distance. This focal distance can be varied within the range of 20 to 30 m simply by moving the concave mirror relative to the lens by about 8.2 cm. Figure 5 is a plot of the focal distance as a function of mirror position.

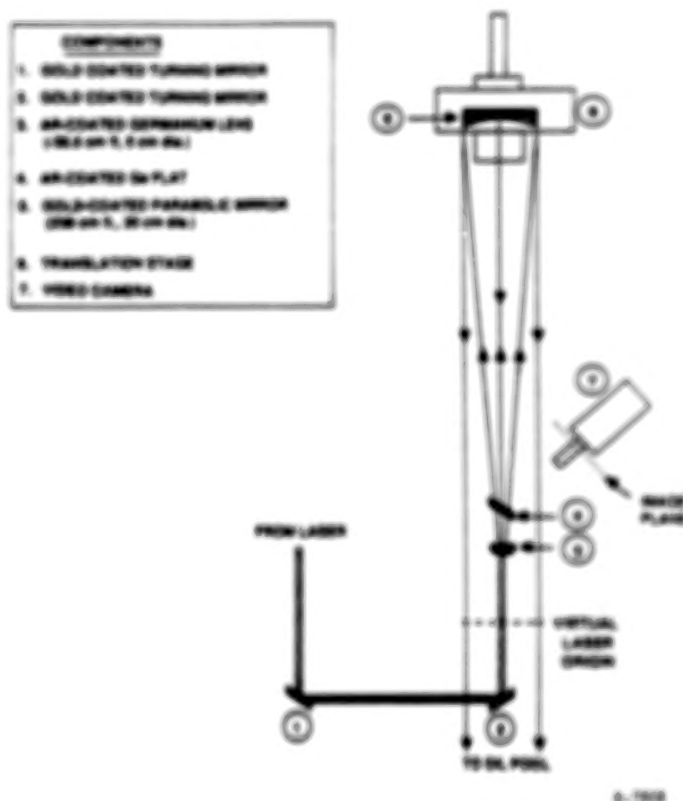


Figure 4 — Laser-Focusing Telescope Configuration.

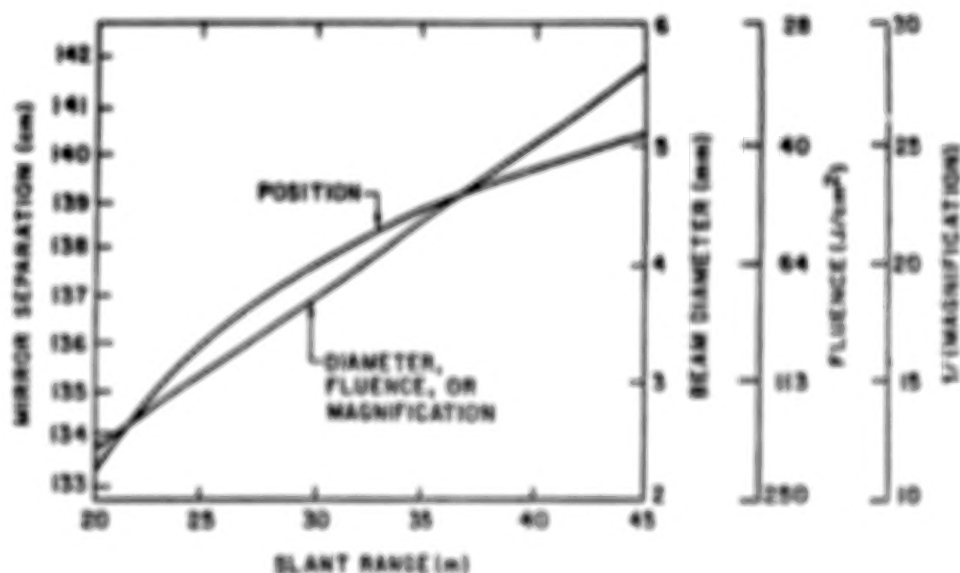


Figure 5 — Mirror Position, Theoretical Beam Diameter and Fluence as a Function of Slant Range From Telescope to Oil Pool.

The components are all mounted on a single table. The pulsed laser beam is directed into the telescope by small flat mirrors (indicated as components #1 and 2). The beam passes through component #3, the anti-reflection (AR) coated germanium diverging lens and thence passes unaffected through a germanium flat, component #4, also coated so as to be non-reflective at the laser wavelength. The beam then impinges on the focusing mirror (#5) after expanding to a diameter of about 20 cm. The now slightly-converging beam is reflected back along its original path, and exits the telescope. Small flat mirrors direct the focused beam to a simulated oil pool in our laboratory. In a helicopter-based system, larger flat mirrors at the telescope exit will serve the same function.

The concave mirror is mounted on a linear translation stage to facilitate focusing. The accuracy with which it must be positioned is determined by the depth-of-field of the focused beam, defined as the range of distances away from the focal point over which the fluence remains sufficiently high to assure ignition. The telescope is designed to produce, at its maximum range, a focal spot having a diameter which is roughly 1/2 that which is required. (At shorter ranges the focal spot is smaller, i.e., the fluence is higher). As a result the theoretical depth of field is about 90 cm, indicating that the mirror must be positioned with an accuracy of about ± 7 mm. To determine and control the position of the mirror, it is possible to either: 1) observe an image of the oil pool through the telescope and vary the position of the concave mirror until the image is in focus; or 2) measure directly the distance between the telescope and the oil pool and calculate or calibrate the appropriate mirror position. Option A is called passive focusing, while option B is active. We are presently exploring the feasibility of employing passive focusing in a helicopter-borne LIOS system.

The passive focusing system works as follows: The diverging lens (component #3) causes the pulsed laser beam to effectively originate on a plane located one focal length behind the lens. The telescope images this plane onto the oil pool. By symmetry, an image of the oil pool is formed by the concave mirror at the effective laser origin. This image is comprised of radiation from scattered sunlight and infrared energy emitted in response to heating by the lasers. It therefore has a fairly broad spectral distribution; it contains energy at wavelengths ranging from the visible to the far-infrared. Much of this energy is split from the laser beam's optical path the germanium flat #4, which, although coated to transmit energy at 10.6 μm without reflection, is highly reflective for wavelengths shorter than about 5 μm . Thus, a visible/near-infrared image of the oil pool is located at the image plane shown in Figure 4. Focusing the telescope is therefore a simple matter of adjusting the concave mirror position until the image of the oil pool is brought into sharp focus.

Though this technique facilitates manual focusing, a helicopter-deployed system requires high-speed automated focusing. We are presently automating the passive focusing process by using a computerized image analyzer to determine when the image is at its best focus and employing that information to drive a motorized position controller and move the concave mirror. Images are captured and digitized with a Data Translation Model 2851 Frame Grabber operating within a Compaq 286 personal computer. The frame-grabber generates a two-dimensional array of data corresponding to the brightness or intensity of the image at each of 512 x 512 pixels. These data are processed numerically to calculate intensity gradients along a set of six intersecting lines, as shown in Figure 6. The position of best focus is defined as that position where the average intensity gradient observed along a line within the image is maximized. One of the six lines, that which has the largest gradients and thus contains the features having the highest contrast, is selected for the focus analysis.

To find the optimum mirror position, the telescope mirror is translated along its entire length of travel and the average intensity gradient along the selected line within the image calculated as a function of mirror position. Typical results are plotted in Figure 7. The mirror is then returned to the position corresponding to the peak value of this curve, which is the position of best focus. Tests have confirmed that when the mirror is positioned using this algorithm it is within ± 1 mm of the position which would be calculated from a direct measurement of the distance to the oil pool surface, i.e., the position indicated by Figure 5.

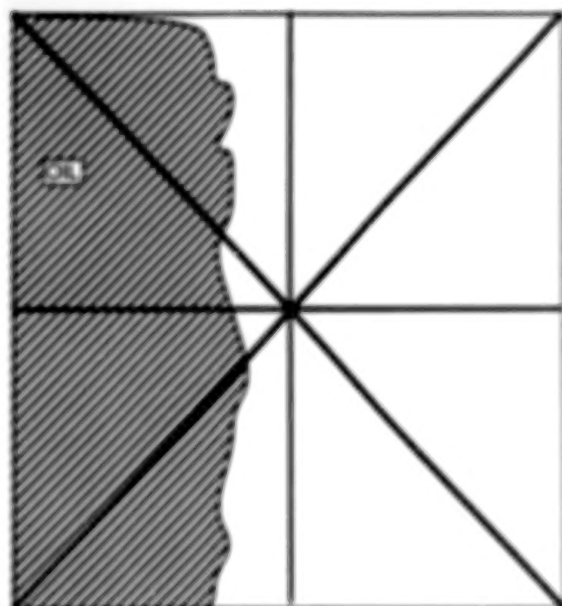


Figure 6 — Illustration of Method Used to Maximize Image Contrast. Intensity Gradients Are Calculated Along the Indicated Lines.

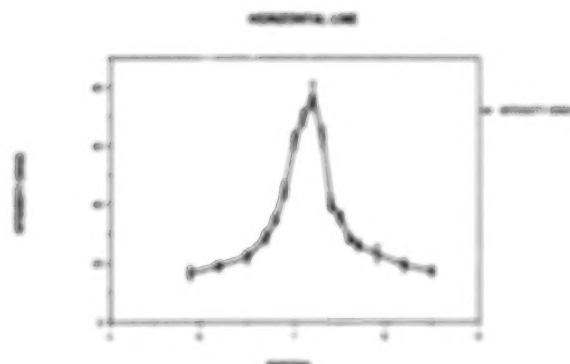


Figure 7 — Average Intensity Gradient Along a Line of Image vs Mirror Position.

This passive focusing algorithm can easily be automated by storing the intensity gradient function in computer memory and programming the computer to drive the mirror to the position of maximum intensity gradient. However, computation of the intensity gradients is rather time consuming. It appears that this method would require several seconds to refocus the telescope after acquiring a new image. This period can potentially be reduced using custom-built analog electronics or a high-speed computer, but both alternatives are expensive. However, by utilizing active focusing, high speed with equally good precision can be had at what will ultimately be a lower cost. An active system uses a laser rangefinder to continually measure the distance to the oil pool and instruct a controller to properly position the focusing mirror based on precalibrated knowledge of a positioning curve such as Figure 5. We anticipate that future developments of the LIOS technique will incorporate this sort of active system.

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Heavy Oil Behavior in the Ocean

Principal Investigator: Merv Fingas
Environmental Emergencies Technology Division
Environment Canada
Ottawa, Ontario, Canada K1A 0H3

Objective: To determine the fate and behavior of heavy oils in the ocean.

Environment Canada and the Minerals Management Service are jointly investigating the fate and behavior of heavy oils in the ocean. Of particular concern is the phenomenon that oil can be overwashed by water, even though its density is somewhat less than water. Also under investigation is the sinking of dense oils and the long-term fate of sunken oil, namely the question of whether it remains in the water column and thus hits a shoreline or sinks to the bottom.

Several reports are in the literature regarding sinking or disappearing of oil slicks. These include the ship ARROW (Forester, 1971), in which large drops of emulsified Bunker C were detected at depths of up to 80 meters; the USNS POTOMAC (Petersen, 1978) incident during which subsurface oil mats were observed; and the IXTOC incident during which mats of emulsified oil were also observed below the surface. The current interest in this phenomenon was sparked by the KURDISTAN incident (C-CORE, 1980 and Reimer, 1981) where sunken pans of Bunker C were noted and some of the oil that was later beached was not observed during surveillance operations in the same area. Several reports of sunken oil in Southern California have been circulated. Recent documented incidents of sunken oil include the KATINA incident (Rijkswaterstaat, 1982) where Bunker fuel submerged but later was beached and the THUNTANK 5 incident in Sweden (OSIR, 1987) where a quantity of 36 to 40 tons of Bunker fuel sank in icy waters. All these incidents involved denser oils or water-in-oil emulsions. Some of these incidents also involved the formation of particles ranging in size from millimeters to meters.

Several studies have been conducted in the past to address various aspects of sinking or submergence in oil spills. In 1982 Environment Canada contracted with Seakem Oceanography to conduct a study of oceanographic conditions suitable for sinking of oil (Juszko and others, 1986). The study resulted in extensive density maps of Canadian waters. It was concluded that there are sufficient pycnoclines and areas of low densities to contribute to some of the observations of historical spill behavior.

In 1984, the Atlantic regional office Environment Canada, with funding from the PERD (Program for Energy Research and Development) project began a 3-year study of the problem of submerged oil. The first year of the study was both a review of the movement of sunken oil and an exploratory study into the mechanisms of sinking.

The study of the subsurface movement of oil was contracted to Seakem Oceanography (Juszko, 1985). The study concluded that the movement forces for subsurface oil could be divided into three categories, macroscale, mesoscale and microscale. The macroscale features include general circulation patterns, seasonal water density distributions, topographically-related features (fronts and frontal circulation, upwelling and rectified flows) and macroscale waves and eddies. Mesoscale features include internal waves, fronts, longitudinal mixing and Langmuir circulation. The primary microscale feature is turbulence. An idealistic four-dimensional model is proposed for the movement of submerged oil. The exploratory study of the mechanisms driving oil submergence was investigated by Don Mackay of the University of Toronto (Wilson and others, 1986). The study concluded that a substantial quantity of oil can be submerged in the water column under steady state conditions. The extent of submergence is increased by: a high oil density occurring naturally or induced by weathering, by the presence of significant surface turbulence, by the formation of small oil particles or drops, and by the formation of water-in-oil emulsions. A complementary exploratory study showed that large oil masses which are slightly less dense than water may be submerged for periods of time by surface turbulence. This important finding was called "overwashing" and was investigated further using wood blocks weighted with lead. It was found that oil and oil surrogates would become overwashed with water when the density was as low

as .90 g/mL and overwashing time increased as the density increased and as the wave height increased. This phenomenon could explain some of the disappearances of oil at sea because even overwashing by as little as a few microns of water renders oil invisible to eye and some forms of remote sensing, especially at oblique angles.

The University of Toronto was contracted to conduct a follow-up study and the overwashing effect was investigated further (Clark and others, 1987). The investigators used oil and oil simulants such as weighted wood, lead packs and plastic balls. Waves were very important in causing overwashing. Overwashing becomes much more pronounced with increasing density. An equation relating these factors was developed:

$$P = \exp(-4/D^2)$$

where $D = KU^3 / (SGD^{2.5} \cdot (1 + L_o))$
 x, K, L_o are constants
 d = depth of submergence
 U = wind speed in m/s
 SGD = the specific gravity difference between the water and the oil
 L_o = the mean diameter of the oil drop
 P = probability factor and overwashing occurs when p is .5

These studies were followed by a series of larger tests in a wave tank and were conducted by S.L. Ross Environmental Research Limited (Buist and Potter, 1987). The findings included a further definition of transient submergence of "deep episodes" which had been observed but not quantified in earlier studies. This phenomenon is described as the plunging of oil particles deep into the water column and residence there for a period of time. The phenomenon is transient and generally does not involve all of the oil in a test situation. An equation for the maximum overwash depth was developed and is the same form as the overwash depth equation but has different constants.

Equations were developed for the overwash depth as follows:

$$d = C \cdot x (\text{den} \cdot a^3 / 2x^3 \cdot \text{diff})^D$$

where d = overwash depth (m)
 c = a constant, determined to be 7.5×10^{-4} and is 2.9×10^{-4} for measuring transient submergence depth
 x = oil particle size (m)
 den = the density of the water (kg/m^3)
 a = wave height (m)
 diff = the difference between the water density and the oil density (kg/m^3)
 D = a constant, is 0.725 and is 0.625 in the case of transient submergence depth

The study also resulted in the development of equations relating the size of the oil pancakes produced under certain conditions. The size of the particle varies directly with the square root of the wave length and inversely with the square root of the wave amplitude.

The probability that oil is at a certain depth can again be predicted as given by the relationship found by Mackay as given above.

These results have been used to prepare simplified nomograms to predict the overwash or submergence depth. Figure 1 presents the overwash or maximum transient submergence depth for fuel oils and Figure 2 presents the same for water-in-oil emulsions.

Heavy or high density oils can become overwashed or sink in water. Oils that have densities of 0.90 to 0.96 can become overwashed with water in higher sea states. Oils with densities of 0.96 to 1.03 will frequently become overwashed with water in higher sea states. The depth at which overwashing occurs

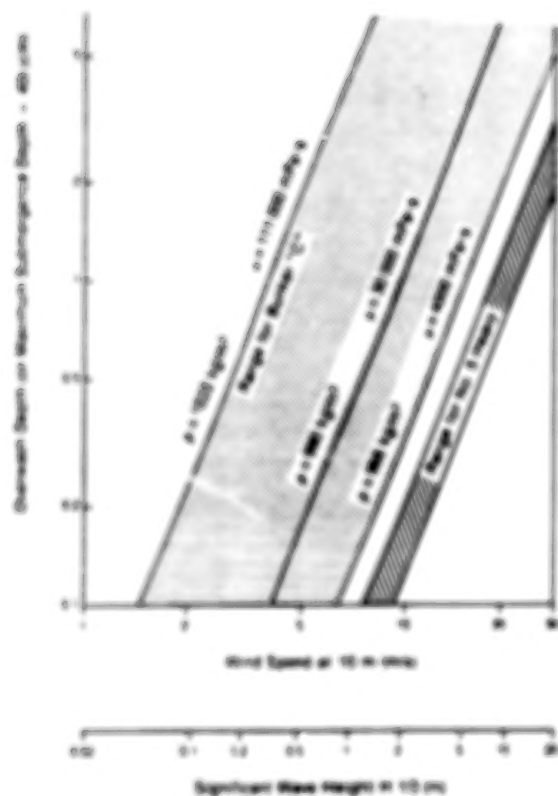


Figure 1 — Nomogram Showing Overwash Depth with Sea Conditions for Fuel Oils.

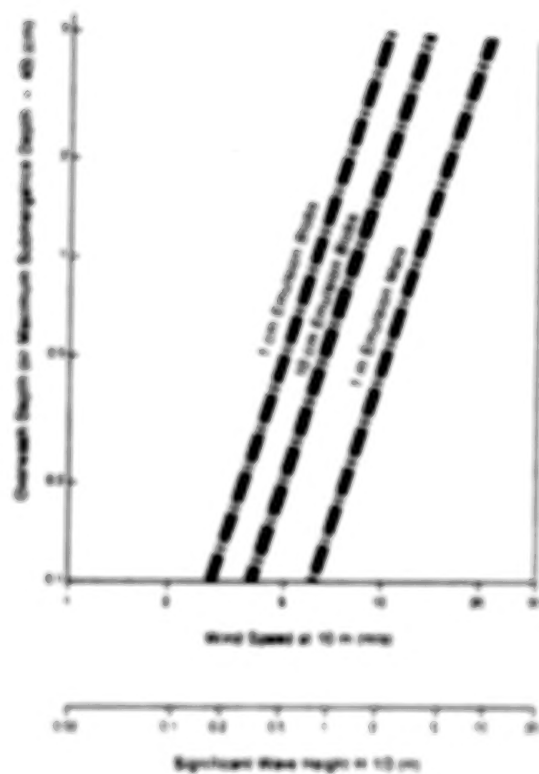


Figure 2 — Nomogram Showing Overwash Depth with Sea Conditions for Water-In-Oil Emulsions.

can be predicted. Overwashed oil will weather differently from oil on the surface and may be difficult to detect as the thin layer of water renders it invisible to remote sensors and human vision at oblique angles.

Heavy oils may also submerge to greater depths than from normal overwashing and this phenomenon has been called transient submergence or deep episodes. The maximum depth to which this occurs is also predictable.

Both overwashing and transient submergence are dependent on the wave height, density difference of the oil, and water and size of the oil particle or blob. The latter can also be predicted by data on wave length, amplitude and oil properties.

The Minerals Management Service and Environment Canada continue to conduct research on this topic. The current issues include: the long-term fate of sunken or overwashed oil, that is, will oil sink to the bottom or will weathering be slow enough to allow the oil to be transported to shore? Another issue to be answered is the long term weathering process applicable to sunken or overwashed oil. Can the length of time that oil floats at neutral buoyancy or is overwashed be predicted so that one knows whether or not a spill of such oil will hit the shoreline or the bottom? Also, how do typical Californian and Canadian heavy oils behave with respect to oils already tested? Three studies are underway at the time of writing. Consultchem of Ottawa, Canada, is investigating the properties of a number of typical heavy oils including two California crudes. The firm also has a contract to investigate the role of photo-oxidation as a long-term weathering process. The University of Toronto is conducting a study to examine all possible long-term weathering for sunken or overwashed oil, to examine the processes responsible for the long-term weathering and, also, to propose an initial weathering model.

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Evaluation of Oil Spill Chemical Additives

Principal Investigator: Merv Fingas
Environmental Emergencies Technology
Environment Canada
Ottawa, Ontario

Objective: To evaluate two new spill treating agents in the laboratory and field situations. One agent, Elastol, is a recovery-enhancer that renders oil visco-elastic; the other agent is a demoussifier*, which prevents the formation of water-in-oil emulsions and breaks down those already formed.

A new oil spill treating agent, Elastol, has been developed for enhancing the recovery potential of oil. When added to oil, the polymer powder renders oil visco-elastic and thus makes it adhesive to oil spill recovery equipment. Elastol is composed of a non-toxic polymer, polyisobutylene, and is not water soluble and hydrophobic. A major study was undertaken jointly by the Minerals Management Service and Environment Canada to evaluate this new spill additive. Studies were conducted in the laboratory, in large scale test tanks, and a major field exercise was conducted off Canada's East coast.

At the time of the above tests, another new spill product, demoussifier, was tested in large outdoor tanks and also at sea. This product, also consisting of a mixture of long-chain polymers, which have no measurable toxicity to humans or to aquatic life, was developed at Environment Canada's River Road Laboratories. The product prevents the formation of water-in-oil emulsions and breaks them once they are formed. A similar product was tested by Environment Canada in earlier tests (Ross, 1986).

The laboratory tests of Elastol involved several different experiments. The effect of a suite of different oils was tested by measuring the time to effect and the degree of elasticity formed. These oils included Prudhoe Bay Crude, Alberta Sweet Mix Blend, Norman Wells, Bent Horn, Hybernian, Diesel Fuel, Tarsiut, Atkinson, Amauligak and a Bunker C mix. All oils displayed visco-elastic properties when treated with doses of 600 to 6000 ppm Elastol. In general, more viscous oils tended to attain a higher degree of elasticity than non-viscous oils, but did so over a longer period of time. No simple correlation between an oil property and Elastol effectiveness could be established. Elastol effectiveness is enhanced by mixing and by higher temperatures, although the latter may be the effect of increasing oil viscosity.

Under low mixing energy conditions, oils exhibited some degree of elasticity within 15 minutes of Elastol application. A high degree of elasticity was not observed until after one hour. Less viscous oils took less time to reach maximum elasticity than more viscous oil. If left to weather, Elastol-treated oil became more elastic with the increasing viscosity of the oil. In fact some samples left for 30-day periods became as elastic as rubber bands sold for stationery purposes. This has been ascribed to the effect of the increasing viscosity of the oil with weathering (evaporation) and not the progressive reaction of the Elastol.

Elastol causes a minor reduction in the rate of oil evaporation, but not significant enough to reduce its flash point. Elastol reduces slick spreading to a limited degree, especially at high concentrations. This effect, about 20 percent, is not believed to have a significant useful result, by itself in real applications. When Elastol is applied in very large doses, >1 percent, the slick would actually contract somewhat, but again, probably not to a degree usable in the field.

The addition of Elastol had either no effect or an inhibiting effect on the formation of water-in-oil emulsions, except in the case of Amauligak and Tarsiut oils, both from the Beaufort Sea region. In a couple of cases, the application of Elastol to emulsified oil actually led to measurable de-emulsification. Application of Elastol to stable water-in-oil emulsions sometimes did not result in significant effectiveness. Testing with commercial de-emulsifiers and the Environment Canada demoussifier, showed that

* The mixing of oil and water forms an emulsion resembling the dessert known as chocolate mousse.

Elastol has no effect on the operation of these chemicals and thus these products could be used together.

Elastol reduces chemical dispersant effectiveness by as much as an order of magnitude. Elastol also reduces natural dispersion of oil into water by as much as three orders of magnitude. This property, while superficially appearing negative, is actually quite useful. If Elastol is used in situations where the aquatic life is very sensitive and important, it could reduce water concentrations of oil in the water sufficiently to minimize damage.

A die swell apparatus was developed to provide measurement of elasticity. The instrument displayed good sensitivity to polymer concentration and to the degree of observed elasticity. The instrument could also be used in field conditions and displays relative insensitivity to debris and water in the oil.

An application device for each of the two products was designed, as commercial devices do not exist for delivering treatments at the low ratios necessary. Elastol would be tested at treatments from 500 to 5000 ppm and the demoussifier would be tested from 150 to 2000 ppm. The search for commercial devices revealed that no suitable devices could be found but that sandblaster-type devices could be modified. A Sears commercial blaster was modified so that it could spray low quantities. One modification was necessary for the solid Elastol, and another for the liquid demoussifier. The applicator operation was tested on each product to ensure that uniform spacial distribution was achieved and that application rates could be controlled over the necessary range by adjusting the air pressure and applying the product from a boat travelling at approximately 3 knots. A series of test tank runs were performed with the new applications to ensure that results obtained previously with hand distribution techniques and with pre-mixing were the same as the present results. Success was achieved in all cases. No detrimental effects were noted during application of either product, such as had been noted with dispersants where herding and other phenomena decreased measured effectiveness very dramatically (Bobra and others, 1988).

Part of this study involved large-scale tank testing of both products. The Esso test tank in Calgary, Alberta, was used for these tests. The tank has dimensions of 15 m by 19 m with a depth of .8 to 2 m. Two test days were devoted to demoussifier and two to Elastol. Testing was conducted in two boomed areas inside the tank. This permitted the simultaneous testing of a control and a treated slick at the same time. The demoussifier prevented the formation of water-in-oil emulsions in both test days and did so at ratios as low as 1:2000 or at 500 ppm.

Elastol was added to a test crude oil at the 4000 ppm level and the test slick released several hours later when the oil was highly elastic. Despite this high elasticity, the oil was of insufficient thickness to burn. The oil was recovered by a rotating disk skimmer and Elastol increased the recovery rate of this unit significantly. In fact the maximum pump rate could not pump all the oil being recovered. On the fourth day of testing, crude oil was treated with 2000 ppm Elastol and recovered with a skimmer. The recovery rate was, again, high and exceeded the capacity of the pump to remove it from the skimmer head. On this particular day, the oil in the untreated boom had formed an emulsion. This was treated with demoussifier, as was the Elastol-treated slick, to ensure that this did not affect the test results. The demoussifier broke the emulsion in the untreated slick and no emulsion formed in the treated slick; nor were any other effects noted. During the first two trial days, the use of demoussifier reduced the effectiveness of the recovery operation significantly. Thus it was concluded that, on a preliminary basis, demoussifier and Elastol could be used together productively.

The large-scale tests showed that there were no scaling effects for either the Elastol or the demoussifier. Both products worked well for the purpose intended. Elastol increased the visco-elasticity of the oil and greatly increased the recovery potential of the oil skimmer. Elastol did not, however, reduce the spreading or increase the thickness of the slick sufficiently to allow direct burning on open water. Demoussifier prevented the formation of water-in-oil emulsions and could also break emulsions already formed. Demoussifier, however, causes the oil to be less adhesive and lowers the recovery rate of skimmers. The products can be applied together to achieve both positive results.

The tests conducted in the tank were repeated on 5-barrel slicks during a field trial 50 miles off Nova Scotia (Seakem, 1988). Five slicks were laid to test each of the products. Each product was tested in a premixed and an application-at-sea mode, to ensure that application effects were not important. Table 1 summarizes the treatments and results of the trial.

Table 1.

DEMOUSSIFIER TRIALS				SAMPLE 1				SAMPLE 2			
SLICK	TREATMENT	TIME	VISCOSITY	WATER CONTENT	COMMENTS	SLICK	TREATMENT	TIME	VISCOSITY	WATER CONTENT	COMMENTS
1	UNTRT	0:00	105000	0.40	NO MOUSSE FORMED	1	UNTRT	0:00	105000	0.40	NO MOUSSE FORMED
2	2500	0:00	27000	0.40	NO MOUSSE FORMED	2	2500	0:00	27000	0.40	NO MOUSSE FORMED
3	5000	0:00	6700	0.40	HEAVY MOUSSE	3	5000	0:00	6700	0.40	HEAVY MOUSSE
4	10000	0:00	22000	0.21	MODERATE MOUSSE	4	10000	0:00	22000	0.21	MODERATE MOUSSE
5	20000	0:00	10000	0.10	NO MOUSSE OBSERVED	5	20000	0:00	10000	0.10	NO MOUSSE OBSERVED
6	40000	0:00	5000	0.05	NO MOUSSE OBSERVED	6	40000	0:00	5000	0.05	NO MOUSSE OBSERVED
7	80000	0:00	2000	0.02	NO MOUSSE OBSERVED	7	80000	0:00	2000	0.02	NO MOUSSE OBSERVED
8	160000	0:00	1000	0.01	NO MOUSSE OBSERVED	8	160000	0:00	1000	0.01	NO MOUSSE OBSERVED
9	320000	0:00	500	0.00	NO MOUSSE OBSERVED	9	320000	0:00	500	0.00	NO MOUSSE OBSERVED
10	640000	0:00	200	0.00	NO MOUSSE OBSERVED	10	640000	0:00	200	0.00	NO MOUSSE OBSERVED
11	1280000	0:00	100	0.00	NO MOUSSE OBSERVED	11	1280000	0:00	100	0.00	NO MOUSSE OBSERVED
12	2560000	0:00	50	0.00	NO MOUSSE OBSERVED	12	2560000	0:00	50	0.00	NO MOUSSE OBSERVED
13	5120000	0:00	25	0.00	NO MOUSSE OBSERVED	13	5120000	0:00	25	0.00	NO MOUSSE OBSERVED
14	10240000	0:00	10	0.00	NO MOUSSE OBSERVED	14	10240000	0:00	10	0.00	NO MOUSSE OBSERVED
15	20480000	0:00	5	0.00	NO MOUSSE OBSERVED	15	20480000	0:00	5	0.00	NO MOUSSE OBSERVED
16	40960000	0:00	2	0.00	NO MOUSSE OBSERVED	16	40960000	0:00	2	0.00	NO MOUSSE OBSERVED
17	81920000	0:00	1	0.00	NO MOUSSE OBSERVED	17	81920000	0:00	1	0.00	NO MOUSSE OBSERVED
18	163840000	0:00	0.5	0.00	NO MOUSSE OBSERVED	18	163840000	0:00	0.5	0.00	NO MOUSSE OBSERVED
19	327680000	0:00	0.2	0.00	NO MOUSSE OBSERVED	19	327680000	0:00	0.2	0.00	NO MOUSSE OBSERVED
20	655360000	0:00	0.1	0.00	NO MOUSSE OBSERVED	20	655360000	0:00	0.1	0.00	NO MOUSSE OBSERVED

The demoussifier trials were performed by laying down a five-barrel oil slick, treating it with the product at the ratio designated, taking samples at subsequent times, and measuring the water content and the viscosity of the product. One slick was left untreated throughout as a control and another slick was left to form mousse (water-in-oil emulsion) and then treated at the 240 minute interval to test the demoussifier's ability to break emulsion at sea. As can be seen by the dramatic reduction in viscosity (105000 to 22600 cSt) over the 30-minute period between samples, the product worked well to break the emulsion. The product also worked well over the five hour test period to prevent the formation of emulsions. This is also illustrated in Figure 1 which shows that there is a strong correlation between the viscosity and the amount of treatment. The greater the treatment, the less the viscosity, because of the lesser water content. The water content was also measured and was universally high, including those slicks that visibly did not form water-in-oil emulsions. Although water content is indicative of the formation of water-in-oil emulsification, the stability of the emulsion would have to be measured since the non-emulsified oil did lose water slowly. The water content of the slicks is interesting in that all the slicks laid out, over the two day test period, rapidly took up water, including those slicks that were treated with Elastol. This was noted despite the fact that the oil viscosity was higher, but not as high as that expected from an emulsion and the oil did not have the appearance of an emulsion. The appearance of the unemulsified oil is also significant, the water droplets were often of sufficient size to be seen in this oil. Emulsion appears reddish-brown, has a high viscosity and the water droplets are too small to be seen.

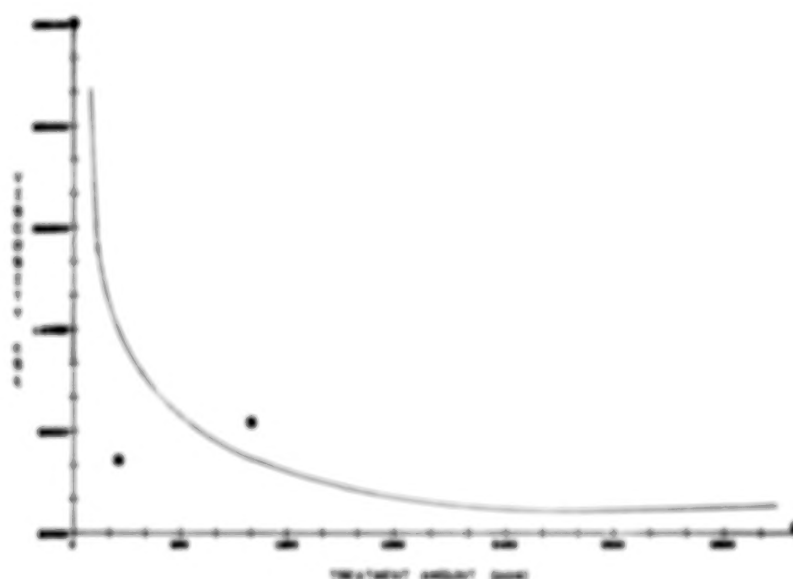


Figure 1 — The Effect of Demoussifier Application on Viscosity.

The Elastol tests were performed in an analogous manner, with one control slick laid and one slick being pretreated to test the effect of at-sea treatment. The slicks were sampled periodically, and both viscosity and elasticity measured immediately on board the ship. Elasticity was measured using the die swell technique in which oil is pushed through a small opening and the fluid responds to this by swelling to a size corresponding to its elasticity. This is measured by photographing the swell, measuring with a vernier caliper and comparing untreated versus treated oil to yield a ratio which is described as "elasticity" in this paper.

The elasticities of the treated slicks were significantly higher than untreated slicks and corresponded to those expected in the laboratory. In fact, elasticities in the case of higher doses, actually exceeded laboratory results. This unexpected result is probably due to the better mixing achieved in the field situation. This is shown in Figure 2. Interestingly, the doses and elasticities in the field appear to be linear, a phenomenon that has not been noted before.

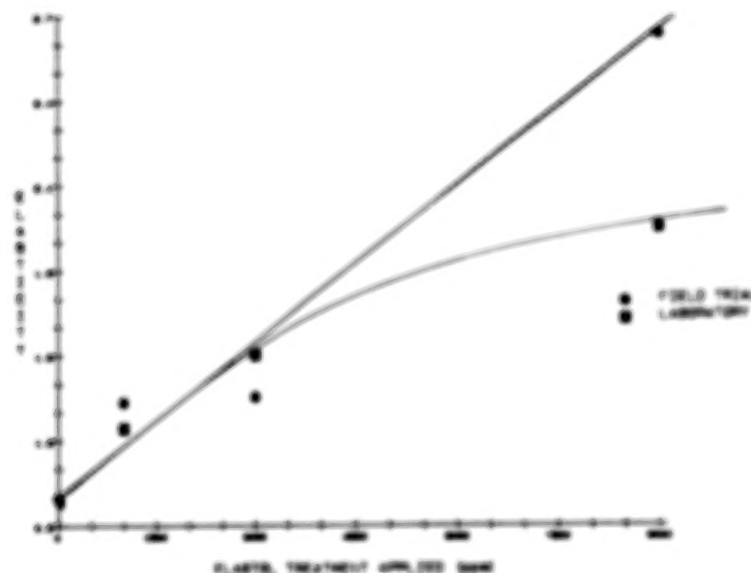


Figure 2 — Elasticity of Oil After Elastol Treatment.

The elasticity of the oil was sufficient to cause the stringing of the product when samples were recovered. This is indicative of a very high state of elasticity and would result in high oil recovery rates if a skimmer was used. The elasticity appeared to be uniform throughout the slicks despite the typical non-uniform distribution of treating agent at sea.

The slicks were monitored by a remote sensing airplane, the analysis of slick areas is not complete at time of writing, however those slicks treated with Elastol appeared to be smaller and the size of the slick appeared to correlate well with the amount of Elastol. In fact, one was able to immediately distinguish slicks by their size, the 9000-ppm-treated slick being the smallest.

Summary and Conclusions

1. Elastol functioned well in the laboratory, test tank and in field situations; it caused oil to become visco-elastic in all applications,
2. Elastol is able to float with and mix with oil so that application is not critical as it is with dispersants,
3. Demoussifier has the same application insensitivity as does Elastol,
4. Elastol functions well to improve oil skimmer recovery,
5. Elastol does slow down and retard slick spreading, however this effect, for physical

- reasons, is not sufficient for countermeasures purposes such as direct ignition of oil on water,
6. The demoussifier prevented emulsion in the test slicks over the five hour test period,
 7. The demoussifier broke water-in-oil emulsions in 10 to 15 seconds after application,
 8. Application effects, such as herding, loss effectiveness, etc., often noted with dispersants, were not noted at all with either product,
 9. Water content is not a good indicator of mousse formation as all slicks at the offshore trial accumulated a large amount of water. Stable mousse formation is indicated by a stable water content, small water droplet size, red coloring and a very high viscosity.

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The 1987 Newfoundland Oil Spill Recovery Experiment

Principal Investigators: E.J. Tennyson
Physical Scientist
Technology Assessment and Research
Branch
Minerals Management Service

H. Whittaker
Head, Engineering Section
Environmental Emergencies Division
Environment Canada, Ottawa, Ontario

Objectives: To evaluate existing oil spill containment and recovery technology and procedures, and to verify a nonpolluting performance evaluation protocol for offshore oil spill containment booms.

A joint Canadian-United States exercise involving the intentional oil spill of 18,000 U.S. gallons was conducted on September 24, 1987, off St. John's Newfoundland to evaluate the containment and recovery capability of three booms and skimmers. The spill also provided an opportunity to verify a nonpolluting performance evaluation procedure for offshore oil containment booms. The spill was conducted approximately 25 nautical miles east of St. John's. The ocean dumping permit required south-southwest currents and westerly winds (to minimize the chance of shoreline contact), water depths of at least 100 meters, a site at least 25 nautical miles from shore, and an area to be within 2 to 3 hours steaming from St. John's. The center of the area selected was 47 degrees, 40 minutes North latitude, and 52 degrees, 03 minutes West longitude.

A crude oil similar to typical high wax Grand Banks crude was unavailable. Brent crude from the North Sea was obtained and treated by adding 1 percent slack wax, by volume, to yield an oil of similar physical properties. The modified oil had a density of 839.8 kg/m³ and a viscosity of 20 m Pas at 12 degrees C (Ross, 1987a).

Meteorological conditions were recorded on the Canadian Coast Guard (CCG) Cutter Grenfell at 15 minute intervals. These included corrected wind velocities and air and water temperatures. A wave rider buoy was deployed at the test site but failed to function during the exercise. Consequently, sea conditions were estimated, with reasonable agreement, by various trained observers.

The test plan called for the sequential deployment of three booms as follows: A 250 meter length of the specially instrumented Oil and Hazardous Material Simulated Environmental Test Tank (OHMSETT) boom would be deployed in normal catenary. Approximately 18,000 gallons of treated Brent crude would be spilled by the command/recovery ship Terra Nova Sea into the catenary. The oil would be held in the boom for approximately 1 hour while boom freeboard and draft data and visual observations of oil retention were recorded. During this period, 200 meters of the Canadian Coast Guard's RO-BOOM would be deployed behind the OHMSETT boom. The tow speed would be increased to "significant loss" speed (0.5-1.0 knot), a tow velocity which would permit oil to circulate under and over the boom. One end of the boom would then be released and the oil discharged into the RO-BOOM. Oil would be held in the RO-BOOM for approximately 1 hour while the oil retention capabilities were observed. The St. John's Coast Guard Vikoma Ocean Pack boom, 400 meters long, would be deployed behind the RO-BOOM during the observation period. The last procedure would require significant loss tow speeds to be repeated with the RO-BOOM, and the oil released into the Vikoma.

Oil would be retained in the Vikoma for approximately 1 hour. The Terra Nova Sea would then commence skimmer evaluations. Two skimmers, the Framo ACW400 and an innovative Coast Guard Heavy Oil Skimmer (HOS), would be evaluated for 20 minutes each. The remaining contained oil would be recovered by the skimmer exhibiting the better performance (Ross, 1987b).

The intent of the OHMSETT boom deployment was to verify the hypothesis that the ability of a boom to contain oil is correlated with its ability to sea keep or comply with wave-induced surface motion. If this hypothesis could be verified and quantified, future performance evaluations of offshore containment booms could be restricted to measuring seakeeping capabilities in a wide range of sea states.

No further spills of the 20,000 gallon size of light and heavy oils would, therefore, be required to evaluate each type of boom. Ocean dumping permits are difficult to obtain and intentional oil spill exercises of this magnitude approach the million dollar funding level. In addition, intentional spills also constitute a risk of potential damage to the immediate environment. Clearly, a cost-effective and nonpolluting evaluation procedure for offshore equipment is necessary to develop a predictive capability for the performance of offshore response equipment. Wind conditions desired were sea state 2 to 4 (winds 10 to 20 knots, 1 to 4 foot waves).

The ships and smaller vessels sailed at 6:00 a.m. and proceeded to a location 5.5 miles off Torbay Point. The CCG Grenfell then deployed the OHMSETT boom and passed one end to the CCG Cutter 212 which took the boom in tow. The CCG Cutter 206 then attempted to pick up the trailing end of the boom, a job which took 45 minutes. As soon as the 206 had the end of the boom secured, the two cutters attempted to tow the boom, in a "U" configuration, into a position astern of the Terra Nova Sea. This resulted in the OHMSETT boom immediately beginning to twist on itself, and 1 hour was lost in straightening the boom. Eventually the boom was positioned relative to the Terra Nova Sea and simulated discharge of the oil was carried out. Data collection, without oil, for almost 1 hour followed.

While the OHMSETT boom was being deployed and positioned, the RO-BOOM was deployed from the CCG Sir Humphrey Gilbert and passed to CCG Cutter 214. This procedure took almost 2 hours, and the RO-BOOM was rapidly positioned with respect to the OHMSETT boom because both the Cutter 214 and a Boston Whaler were able to tow the boom at speeds of 5 knots.

With the RO-BOOM in position, the Cutters 212 and 206 commenced to maneuver, presumably to form a "J". The Cutter 206 then snagged the OHMSETT cable in her screws and cut it, disabling herself. This resulted in delay of the exercise while the cable was freed, and because Cutter 214 and an assist boat (a Boston Whaler) were now approaching closely, the Cutter 212 took the boom and Cutter 206 in tow and cleared the area so as not to impede the exercise.

During the period in which the RO-BOOM was being deployed, the CCG Grenfell deployed the Vikoma boom. Once the simulated oil release was over, the Terra Nova Sea took the other end of the boom and the vessels formed a catenary. After holding position relative to the RO-BOOM for a short period, the ships formed a "J" with the boom and practiced deploying the skimmers.

All ships returned to harbor by 5:00 p.m.

Several meetings of the senior people involved in the exercise occurred between September 21 and September 23, 1987. It was decided to remove Cutter 206 from the exercise. The Boston Whaler was able to tow and hold the boom in sea state 1, but it was recognized that this would be difficult with oil in the desired weather. The Newfoundland Fisheries department had provided a vessel, the Bernier, and it was decided to use her and a second chartered offshore supply vessel (OSV) to tow the RO-BOOM.

Concern was expressed that the weather might, surprisingly, be too calm on September 24, the day which looked best for the actual trial. It was, therefore, decided to interchange the OHMSETT and RO-BOOMS to take advantage of the higher winds and waves expected later in the day.

The long time required to deploy the RO-BOOM from the Sir Humphrey Gilbert led to a decision to deploy that boom from the second OSV, the Triumph Sea. Repairs were carried out on the OHMSETT boom instrumented cabling, and the boom with instrumentation was functional by 5:00 p.m. on September 23.

Since the Terra Nova Sea had oil recovery tanks on board, it was decided to dispense with the dumb barge and to release the oil directly from that OSV.

The Triumph Sea and the Bernier sailed at 3:00 a.m. All other vessels sailed at 4:00 a.m., and everyone was on station by 6:45 a.m. The Triumph Sea commenced deployment of the RO-BOOM enroute, and by 7:30 a.m. the boom was ready to receive oil. Once the OHMSETT boom was deployed, at 8:15 a.m., the oil was pumped into the RO-BOOM under supervision from the helicopter and a small boat.

All oil was in the boom by 9:00 a.m.

It was decided to give the news media a chance to view the test from the air and this was done from 9:00 a.m. to 10:00 a.m. During this period, the Cutters 212 and 214 attempted to pull the OHMSETT

boom into proper position in the wake of the RO-BOOM and to keep it there. Every attempt to move the boom, in a catenary configuration, in the 15 knot winds blowing at the time resulted in the boom twisting. As a result the OHMSETT boom fell progressively further behind the RO-BOOM.

At 10:30 a.m. the oil in the end of the pocket of the RO-BOOM was 30 cm thick, the wind was 15 knots, and some splash-over and significant drainage under the boom were occurring. The vessels, therefore, formed a "J" and released one end of the boom to allow the oil to flow into the OHMSETT boom. The OHMSETT boom was approximately 1 km astern, and the vessels were having trouble towing that boom in a catenary without it twisting. It was, therefore, decided to direct the cutters towing the OHMSETT boom to the oil by helicopter, keeping the boom in a straight tow. After 20 minutes, the cutters were adjacent to the thick oil, and, after a further 20 minutes, approximately 80 percent of the thick oil was in the OHMSETT boom. The remaining 20 percent was contained in the Vikoma boom. Data collection on the OHMSETT boom started as soon as the oil was captured and continued for 56 minutes. The cutters then stopped across the path of the vessels towing the Vikoma boom and released one end of their boom. The oil spilled into the Vikoma boom catenary, and one cutter trailed the OHMSETT boom at the throat of the catenary allowing the waves to wash the oil into the Vikoma boom.

The Grenfell and Terra Nova Sea towed the oil filled Vikoma boom for approximately 1 hour. During this time, the wind freshened to 15 knots to 20 knots. The boom was moving over 1.1 knots relative to the sea, and some oil was lost (approximately 3 mm thick). The Grenfell then attempted to move ahead to form the "J" for the skimmers. Not being very maneuverable, she quickly reached 3.4 knots and the oil was lost.

With the oil now lost, the weather abated slightly. The RO-BOOM was still streaming astern of the Triumph Sea so it was decided that she and the Bernier would form the boom into a catenary and attempt to recover the oil by steaming downwind. The helicopter was lost to the exercise for approximately 1 hour at this time. In the interim a small boat was used to guide the tow vessels into the heaviest portions of the slick. When the helicopter returned, it was able to determine from its vantage point that the vessels with the RO-BOOM were adjacent to some of the oil though they were unable to see it. They were, therefore, directed from the air and small boat, and managed to collect 80 to 90 percent of the thick oil which was on the surface at the time.

Oil was successfully contained and recovery was attempted using the three skimmers on board the recovery-command vessel. The first skimmer, HOS, was deployed and no measurable recovery was observed. The oil used was modified by adding petroleum wax so that it would resemble a typical Grand Banks crude oil. This type of oil is uncharacteristic of most crudes in that it possesses low adhesive properties. Therefore, oleophilic skimmers, which depend upon the adhesive nature of the recovered oil, do not perform well with high paraffin-based oils. This was again proven with the oleophilic HOS skimmer. The skimmer was recovered after several trained observers were satisfied that it had sufficient evaluation time in the contained slick. Problems with the inability of the support arms used to suspend both the HOS and Framo skimmers and adjust to the roll of the vessel in the short period waves, resulted in both skimmers being frequently submerged so that oil and water were washed into their sumps.

The second skimmer, the Framo ACW-400, was deployed. The overall rate of oil recovery was 60 gallons per minute, there being unknown amounts of oil recovery because of frequent partial submergence.

At this point, it was decided by the on-scene commander that skimmer evaluation was complete. Additional measures were needed to ensure recovery of the remaining contained oil because the weather was deteriorating and the night approaching. Accordingly, approximately 7 pounds of the visco-elastic agent "Elastol" were spread from an 8 ounce styrofoam coffee cup into the estimated 7,400 gallons of oil and oil-water emulsion in the containment boom. Elastol was added because previous research supported by the Minerals Management Service and Environment Canada had shown that the elastic and adhesive properties of the oil could be increased by addition of the agent, thus making the oil more readily capturable with these types of skimmers. The Framo ACW-400 was retrieved from the slick as the Elastol was added, and because of rough weather and the lateness of the day, the skimmer was not redeployed.

The weir-type skimmer, Pharos Marine GT-185, was deployed into the treated slick; it recovered near capacity rates of 85 gallons per minute of oil and oil emulsion, there being no free water. This recovery rate was higher than anticipated and may have been even higher if the oil had been untreated. Treatment significantly increased the viscosity of the oil. The skimmer was removed from the slick.

The HOS skimmer was redeployed and yielded a recovery rate of 50 gallons per minute even though a portion of the oleophilic fabric on one of its two drums was damaged. Debris was collected at this time in the venturi system used to measure recovery fluid flow rates. The debris may have contributed to the subsequent failure of the HOS skimmer return hose. No flow-rate measurements were taken before the failure. Visual observations on the amount of oil adhering to the oleophilic fabric of the HOS skimmer indicated that recovery rates were significantly increased by the addition of Elastol.

Operations were suspended because of the increasing sea states and advancing darkness.

An overflight of the area by helicopter was carried out during the skimming operation revealing a sheen approximately 2.5 by 0.5 nautical miles with 3 patches of brown oil. It is estimated that no more than 260 gallons of oil remained in the thick patches. A further flight 18 hours later showed that only small brown patches and sheen remained, and this was rapidly dispersing.

Conclusions

- Thorough proficiency in the use of recovery equipment is essential for effective operations. Routine practice is required to achieve this degree of readiness.
- Large volumes of oil (at least 20,000 U.S. gallons and preferably 80,000 gallons) are necessary to realistically evaluate performance of offshore response equipment.
- The use of helicopters to direct the placement of tow vessels and the use of small vessels to monitor and advise on boom conditions are essential to maximize the efficiency of conventional recovery operations.
- Accurate measurements of the meteorological and sea conditions are necessary for accurate analysis of the evaluations.
- The requirements for slow-speed towing and maneuvering of large containment booms necessitate the use of vessels with variable pitch propellers, bow thrusters, and good seamanship.
- It is not possible to form a recovery configuration using two vessels, towing upwind. A third vessel is necessary for recovery of the oil in the catenary.
- Upwind collection proved impossible when winds approached 15 knots. This is consistent with many past observations for containment operations conducted upwind.
- The upper meteorological and sea state limits for downwind containment and recovery were not reached during this test.
- Contained oil will be lost if shipboard discharges such as cooling water impinge upon the slick during recovery operations.
- Tankage should be available for recovery of several times as much fluid as discharged to account for the oil and water emulsions and free water recovered.
- Recovery of high wax oils similar to Newfoundland crudes in 10 degrees C water is significantly enhanced by the use of Elastol.

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Evaluation of a Water Jet Barrier in Ice Conditions

Principal Investigator: Francine Laperrière
Environmental Emergencies Technology
Environment Canada
Ottawa, Ontario

Limitations of conventional barriers for containment and deflection of oil spills in currents above 1 knot have promoted the study of alternative systems which generate locally a horizontal surface current to oppose the movement of floating oil. Air jets were tested at FPA's OHMSETT facility (Cohen, Lindenmuth, 1979) but it was shown that a large pressure drop in the duct would preclude the development of an operational barrier. Plunging water jets were also tested at the same facility (Nash, Farlow, 1984). Used with low pressure (150 kPa (22 psi)) and high water volume (300 lpm (80 U.S. gpm)), they showed good efficiency in a deflection configuration. Unfortunately, the logistics increases rapidly with the deflection distance and the current strength. Flat fan high-pressure water jets, horizontally oriented above the surface of the water, which showed potential in tank testing at OHMSETT, were used in an array configuration in rivers and canals (Meikle, Whittaker, Laperrière, 1985). Deflection in currents of about 2 kts was possible even though the system used was not fully optimized but sufficiently operational to test the concept. Alternative uses of this technique were identified and considered for further testing to contain oil in the presence of floating ice, to sweep and protect tidal mud flats, and to burn floating oil in-situ more efficiently.

The evaluation discussed in this report is the containment of oil in the presence of ice.

The objectives of this evaluation of a water jet barrier in ice conditions were (1) the assessment of the impact strength of flat fan high pressure water jets on ice floes in motion towards the deflectors, and (2) the assessment of the distance of influence $\frac{1}{2}$ front of flat fan high pressure water jets used in ice floes as an oil deflector.

Knowing the limitations of Environment Canada's high pressure water jet prototype barrier in clear water, very specific ice and current conditions were sought: 1.5-10 m³ ice floes, low density ice cover, less than one knot current.

Simulation in a tank was not possible because of the large test area required. Desired ice and current conditions can generally be found in some locations on the St. Lawrence River during springtime. Two sections of the river were considered for conducting the testing in the vicinity of Trois-Rivières and Quebec harbors.

Testing was to be accomplished with the help of Canadian Coast Guard ice breakers. Logistic problems related to the assembly/disassembly of the prototype barrier were to be minimized using a vessel to move the barrier to the best test area(s), with the power generation system also on board.

In March 1987, the ice cover on the St. Lawrence River broke-up earlier than usual due to very high temperature and left rapidly towards the Gulf. It affected this evaluation in terms of ice floe availability. The national harbors considered did not experience drifting ice floes by their docks within the time frame planned for the testing. Other test areas were looked at on March 24, 1987 (private harbors and sheltered basins) but sudden shifting winds cleared the areas from ice floes before the testing could start.

An attempt to evaluate the barrier was finally made on March 26, 1987 at the St. Charles River estuary, in calm water, near a pier. The ice coverage was about six to seven eights.

The barrier, its possible configurations and the power system, are described in Meikle, Whittaker, Laperrière (1985). A barrier length of 10 m was assembled on the pier and loaded onto the deck of the ice breaker "Bernier" together with the high pressure pump. A short barrier length (half of the usual size) was used because of control and maneuverability difficulties in such ice coverage conditions. The use of a small boat for r/s/zle adjustments and tightening connections throughout the testing was impossible, the water was too cold. Both ends of the barrier were attached to a rope and the barrier was lifted on board using a crane when adjustments were required.

The barrier could not be tested while the vessel's propellers were operating. The turbulence generated cleared the water surface of ice for a 12-15 m radius around the vessel.

Because of the high density ice coverage, the water surface was first cleared around the vessel, the barrier was then deployed along the vessel, using a crane. The jets were operated at 6895 kPa (1000 psi) and the ice floes were pushed back towards the barrier using a motorized barge, Figure 1.



Figure 1 — Operation of the Waterjet Barrier.



Figure 2 — Slow Deflection of the Ice Flow.

At a pressure of 6895 kPa using 57 lpm/jet (15 US gpm/jet), the jets could not push away the floes already touching the floats. When the flows were pushed in front of the first barrier's jet, very slowly the ice floes were deflected, Figure 2.

The distance of influence on the ice floes in front of the barrier was difficult to estimate because floes could never be brought towards the barrier the same way. However, during the deflection of an ice floe of about 3 m², 1 m thick, 0.15 m above the water surface, a deflection distance of 1.8-2.4 m in front of the nozzles was kept clear using a pressure of 6895 kPa, Figure 3.

The influence of the jets on spilled peat moss between and behind isolated ice floes could not be



Figure 3 — Keeping the Ice Flow Clear.

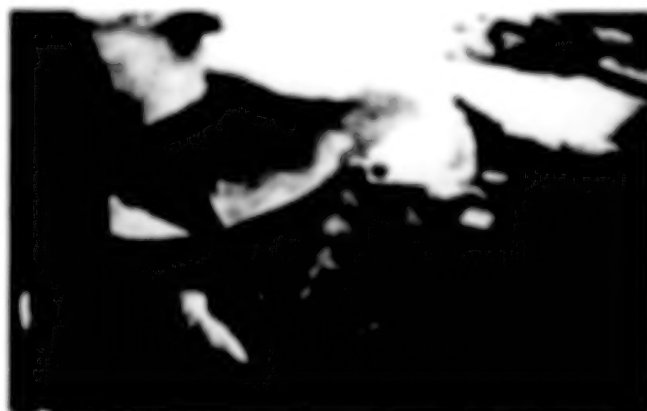


Figure 4 — Absence of Ripples Near Ice Flow at Greater Distance from Waterjet.

verified. Difficulties controlling the number of ice floes in front of the barrier and the clearance between them prevented specific measurements. The jets were deflecting the mass of ice rather than just the peat moss.

On the subject of turbulence on the water surface generated by the jets, when in front of a broken ice mass, in openings of about 0.8 m wide, parallel to the jet, there was some turbulence up to 4.5-6.0 m away from the jets. In openings of 0.3 m wide parallel to the jet, at 4.5 m away from the barrier there were no more ripples on the water surface. No turbulence was noticed behind ice floes with edges perpendicular to the jet, at a distance of about 3 m from the jets, Figure 4.

From previous tank testing with water jets of the same type, aperture, angle and height, we know that air flows generated have a noticeable velocity up to 6 m away. This is not in contradiction with the observations made in the present evaluation. In wide openings among ice floes with edges parallel to the jet, the same turbulence range on the surface of the water was noticed as in the tank testing. In smaller ice openings parallel to the jet, the influence of the edges of the ice seem to be more important since surface turbulence is less noticeable. For openings perpendicular to the jet, the ice edges seem to strongly reduce the water turbulence.

These few observations were done without using peat moss. Observations with peat moss at least, but preferably with oil, in a controlled ice environment are required to assess the limitations of high pressure water jets in an ice environment.

Conclusions

This short test showed that although the waterjet barrier had some potential in ice, its current configuration was not suitable. A more rigid system would be required. It is recommended that a system of waterjets, mounted in rigid pipe, which can be affixed to the bow of vessels of opportunity should be investigated. If such a system appears feasible, it should be built and tested in ice.

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Shipboard Navigational Radar as an Oil Spill Tracking Tool

Principal Investigator: E.J. Tennyson
Minerals Management Service
Reston, Virginia

Objective: To investigate the capabilities of shipboard navigational radar to detect and track open ocean oil spill slicks by altering normal use procedures.

The capabilities of two X-band shipboard navigational radar units to detect oil slicks were evaluated during a joint Environment Canada-Minerals Management Service experiment off Nova Scotia, in September 1987. Two series of spills were conducted; each consisted of five releases of 5-imperial-barrels of Alberta Sweet Blend Mix (ASBM) crude and ASBM to which Bunker C oil had been added. The behavior of these slicks was monitored until the slicks had visually dissipated. Radar was used for tracking and the radar images were compared with visual observations when conditions permitted. Winds ranged from less than 10 to over 30 knots during the radar evaluation. Weather ranged from fog-to-rain-to-clear conditions.

The application of airborne X-band and synthetic aperture radar for slick detection is a proven technique, there being a number of worldwide operational units routinely available. Previous evaluation of shipboard radar (Axelsson, 1974) indicated that detection ranges for oil slicks were limited to approximately 1 kilometer even though the radar unit evaluated had a maximum nominal range of 75 nautical miles. Discussions of factors influencing radar imagery routinely describe a critical viewing angle of at least 20 degrees for sufficient reflection to yield a discernable pattern of sea surface conditions (Simonet, 1983). One evaluation of optimal antenna viewing angles (C-Core, 1981) indicated that 30 to 45 degrees from the vertical angle would be required. This lends credence to the findings of Axelsson and appears to explain the previously reported limited oil spill detection range of shipboard radar. However, evaluations during this cruise indicated that clear depictions of slicks are possible at ranges of 12 nautical miles or more.

One explanation of the way radar receives returns from the ocean surface is through back scattering. Microwave back scattering from the ocean surface may be due to Bragg scattering by the short (approximately 5 cm) waves for X-band radar causing a resonance in the microwave return to the antenna. This constructive interference is apparently necessary for discernable depiction of differences in sea surface texture except when breaking waves are present (Milgram, 1988). Bragg scattering is also a function of antenna viewing angle.

This evaluation of shipboard radar was predicated on the damping of short period waves by the slick and the ability of radar to detect and represent differences in the short period wave field.

The joint Environment Canada-Minerals Management Service cruise to evaluate two oil spill chemical additives was conducted from the Canadian Coast Guard Cutter Mary Hitchens on September 9-10, 1987, off Nova Scotia. The results of the evaluation of these additives are reported elsewhere in this report.

Two shipboard radar units were used, coincidentally, to track and monitor each of the ten 5-imperial-barrel oil spills during this exercise. The radars were Sperry MK-340 and Decca 914, the latter having a bright track repeater. The Sperry MK-340 is an X-band radar with a horizontal beam width of 1.9 degrees and nominal ranges of 0.25, 0.5, 0.75, 1.5, 3, 6, 12, 14, 24, 48, and 120 nautical miles. It is a 50 kilowatt unit with an antenna approximately 50 feet above the ocean surface. The Decca 914 is also an X-band radar having nominal ranges of 0.25, 0.5, 0.75, 1.5, 3, 6, 12, 24, 48, and 60 nautical miles. The horizontal beam width is 1.9 degrees. This radar is a 25 kilowatt unit, having an antenna height of approximately 40 feet above the ocean surface.

Initial attempts to track the first five of the 5-barrel slicks over a range up to 12 nautical miles were unsuccessful with radars operating in standard navigational mode. Both units contained sophisticated interference filters to reduce sea return and interference from rain. Approximately two hours were initially required to adjust the gain and sea and rain clutter filters to optimize the representation of the sea

return. Once a relatively homogenous sea return was available on the radar, the areas of diminished sea return representing short wave damping resulting from the oil slick were analyzed. The radar could subsequently be returned to navigational or slick detection mode by activating and deactivating the automatic filter program. The Decca system did not offer the resolution of the Sperry and was less complex to operate so that initial adjustment for optimal sea surface return was more easily accomplished.

No photographic capabilities existed for the Sperry radar screen. The Decca bright track unit, however, allowed a wide range of screen brightness control, and the following photographs were taken of its screen.

Figure 1 clearly shows a mast shadow artifact caused by the mounting of the radar unit just forward and to starboard of the ship's mast. This pie-shaped hole in the sea return was apparent at all times.



Figure 1 — The Mast Shadow Artifact.

Figure 2 shows a five barrel slick which is visible at 11 o'clock (350 degrees relative bearing); the range is 3 nautical miles, winds 15-20 knots. The slick had deteriorated with patches of thick oil and mousse (oil-water emulsion) surrounded by sheen. A freighter had transited the exercise area, discharging oil which produced a 50 meter wide slick from horizon to horizon. This slick is also visible on the figure at 9 o'clock (270 degrees relative bearing).

Figure 3 depicts a slick which is clearly visible from 6 to 7 o'clock (180-200 degrees relative bearing) even though partially obscured by the mast shadow. The slick is very light (mostly sheen). Winds are less than 10 knots. Range to the slick is 3 miles.

Figure 4 shows the mast artifact from 6 to 7 o'clock (180-200 degrees relative bearing). The slick from the freighter is visible at 4 o'clock and 9 o'clock (110 and 270 degrees relative bearing) and is continuous. A heavily dissipated sheen is visible at 12 o'clock (360 degrees relative bearing). Range is 12 nautical miles, winds 25-30 knots.

The Decca Unit did not have the resolution of the Sperry; therefore, the photographs do not offer the detail observed during the evaluations of the Sperry.

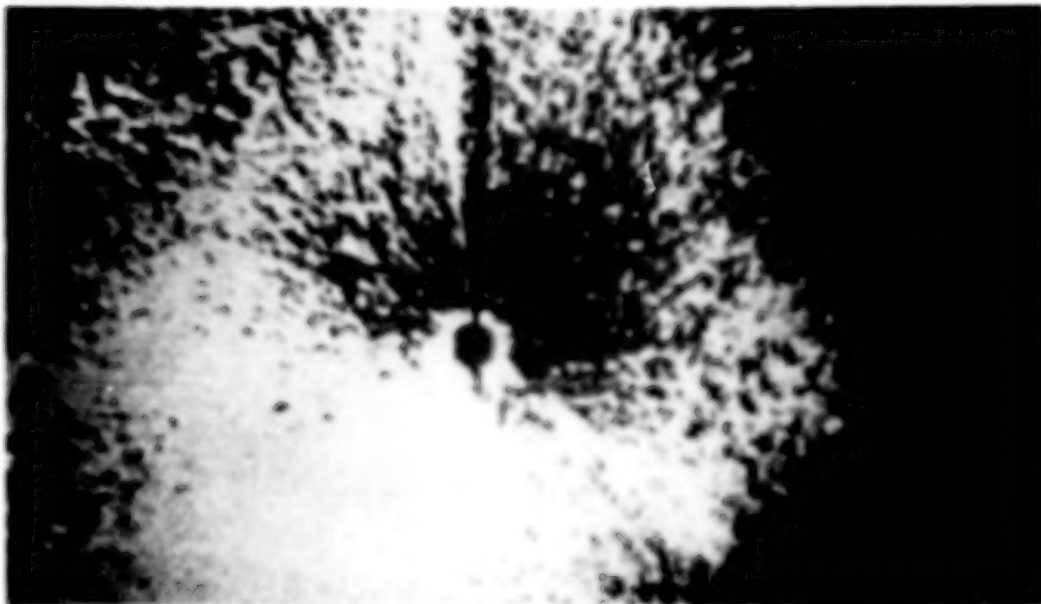


Figure 2 — A Five-Barrel Oil Slick at 3 Miles and That of a Pausing Freighter.

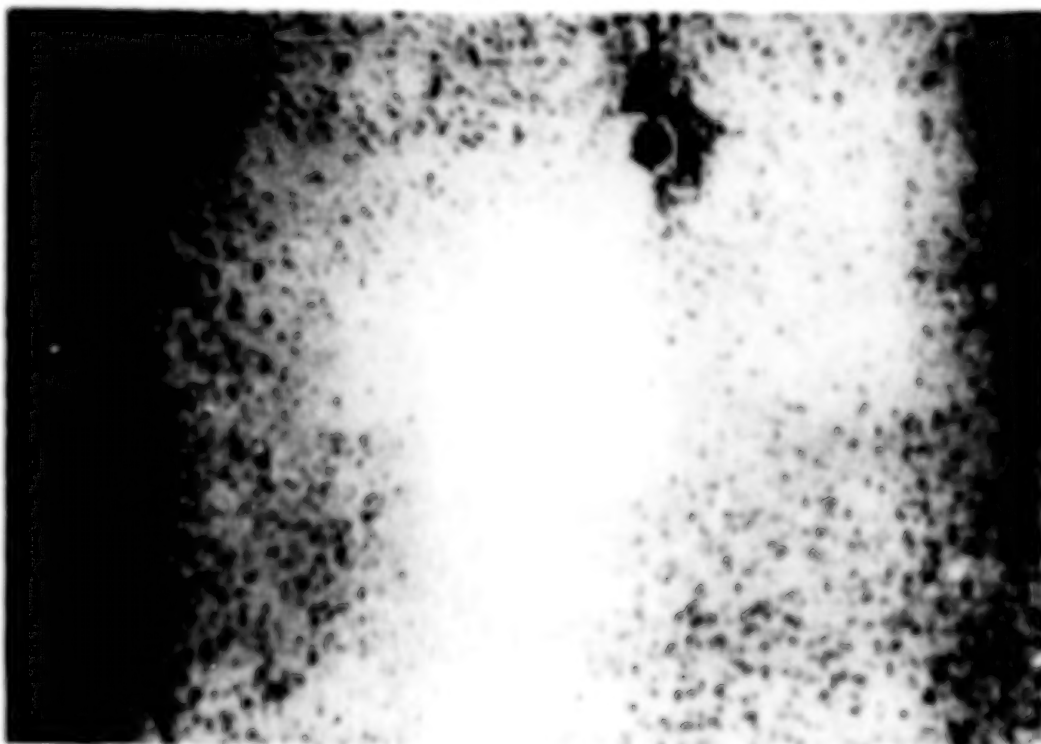


Figure 3 — A Very Light Slick at 3 Miles.

The presence of large swells coupled with breaking wind driven waves obscured the slicks when winds exceeded 30 knots. It is unclear whether relatively old and confused sea states, or the rapid dissipation of the slick under these conditions, was responsible for the loss of detection. Perhaps both contributed to the apparent inability of either radar to find slicks in confused breaking seas at these relatively high wind velocities. Fog and rain had no effect on the detection capabilities of either radar.

There was an apparent correlation between the observed thicker portions of slicks and radar images. As a slick dispersed leaving a sheen, the radar image became more indistinct. The radar technique apparently discerns thicker, more recoverable slicks from less recoverable portions and, therefore, can be used to guide recovery operations.

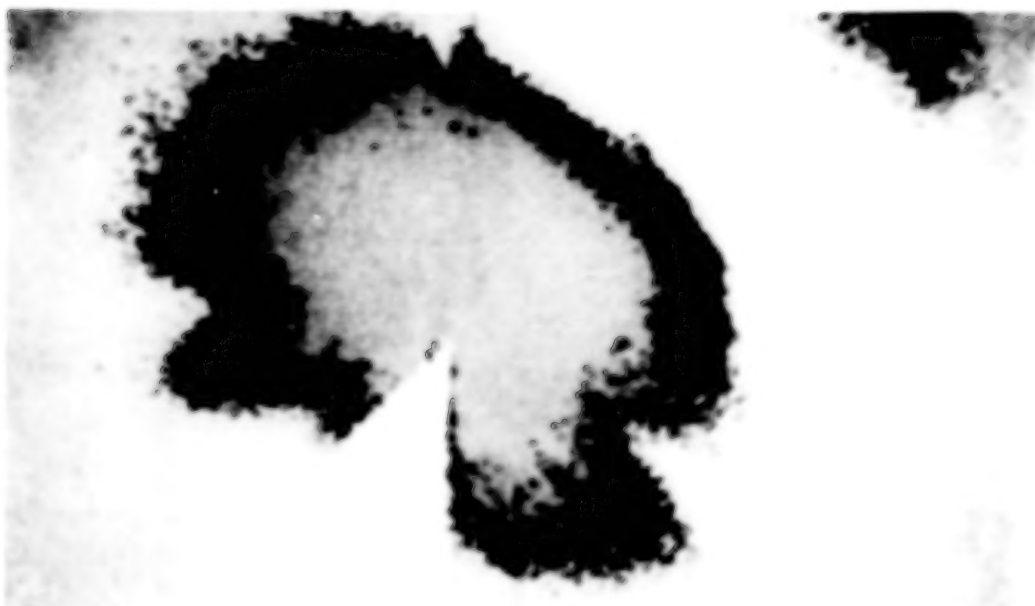


Figure 4 — Heavily Disipated Sheen at 12 Miles.

Conclusions

Shipboard X-band navigational radar can readily detect oil spills in light to moderate sea conditions if properly tuned.

Slicks are clearly detectable in winds up to 30 knots as long as major swells (8 to 10 feet) are not present. (Tests in winds less than 5 knots were not run.)

Requirements for tuning a radar to optimize sea return vary with the complexity of a unit. The higher the complexity the more difficult the initial tuning.

Radar is a readily available tool for use during oil spill response and its use can facilitate slick tracking and eliminate many of the detection problems associated with fog, rain, darkness, and relatively high sea states.

Further evaluation of shipboard navigational radar in a wide range of oils and sea states is required to quantify the limits of this technique.

Disclaimer

The mention of specific products in this report does not constitute or imply an endorsement by the Minerals Management Service or the author.

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Wellhead Fire Suppression With Water Sprays

Principal Investigator: Dr. David D. Evans
Center for Fire Research
National Bureau of Standards
Gaithersburg, MD 20899

Objective: To develop blowout fire suppression technology for offshore oil and gas operations.

The Center for Fire Research (CFR) of the National Bureau of Standards (NBS) is investigating the feasibility of controlling the radiation from, and the extinguishment of, blowout fires by use of a water spray fire suppression system. When water is added to any hydrocarbon fuel fire, even in small amounts, radiation from the flames is reduced. It has been found in this research that when sufficiently large amounts of water are added, simulated gas wellhead fires can be extinguished. Research has focused on analysis of radiation from simulated gas well blowout fires, testing of a prototype water spray fire suppression system with obstructed gas jet fires, and measurement of radiation from combined liquid and gas hydrocarbon jet-flames.

A series of large scale simulated gas wellhead fire suppression tests was conducted in Norman, Oklahoma in 1984 to evaluate the performance of a four nozzle water spray system to extinguish or limit radiation from the fire (Evans and Phennig, 1985). An arrangement of four water spray nozzles placed symmetrically about a 0.1 m (4 in) diameter gas outlet to spray water vertically into and around a methane gas jet-flame was tested. It was found that an unobstructed nominally 200 MW (5.6 m³/s (17 MMSCF/D¹) methane) jet-flame could be extinguished under no wind conditions with a water flow rate of 8.1 liters/s (129 GPM), but would continue to burn with a lower water injection rate of 5.4 liters/s (86 GPM). For scaling purposes and application of the results to other fires, these results can be recast in terms of the water spray to methane mass flow rate ratio. In these terms the fire was extinguished at a mass flow rate ratio of 2.2 and continued to burn at a ratio of 1.6. In the case of the fires not extinguished by the water spray, the radiation from the flame was reduced.

The flame structure and radiation properties of these large methane jet-flames were predicted using a laminar flamelet concept for turbulent flames and a narrow band radiation model developed by Faeth at the University of Michigan (Gore and others, 1986). In this analysis, only data prior to water spray injection was used. The laminar flamelet analysis permits prediction of turbulent flame temperatures by analyzing turbulent flames as if they were equivalent to wrinkled laminar flames. Predicted and measured flame temperatures as a function of distance from the gas outlet are shown in Figure 1. Separate predictions are shown for the two representations of the initial flow conditions of the escaping gas—divergent nozzle and momentum velocity methods. In each case, both time- $\overline{[T]}$ and density weighted (Favre)- $\overline{[T]}$ (Bilger, 1976) averaged predicted mean temperatures are shown. Three experimental results all of approximately the same nominal 200 MW energy release rate test conditions except for minor wind variations are shown to compare to the calculated result for 200 MW and no wind. Wind disturbances during the tests deflect the flame off axis, causing measured temperatures to be too low, particularly at locations far from the gas outlet. The comparison between predictions and measurements is encouraging. Measured maximum temperatures are roughly 200 K below the predictions, which is reasonable in view of probable thermocouple error from radiation heat losses and the effects of wind disturbances.

Predicted and measured flame radiation heat fluxes at five positions around the flame are contained in Table 1. Only one prediction is given for the nominal condition of 200 MW energy release rate. For comparison purposes the data from the three tests are averaged. Predictions in Table 1 generally underestimate the experimental results. The average discrepancy between predictions and measurements in Table 1 is 20 percent, which is quite good in view of the fact that ambient wind disturbances are not accounted for in the predictions. Also turbulent radiation interactions, that were ignored in the calculation, tend to increase calculated radiation levels from the mean property predictions shown here by roughly 10 percent for a methane/air flame.

¹ Million standard cubic feet per day at 1 atm. and 15.5 °C.

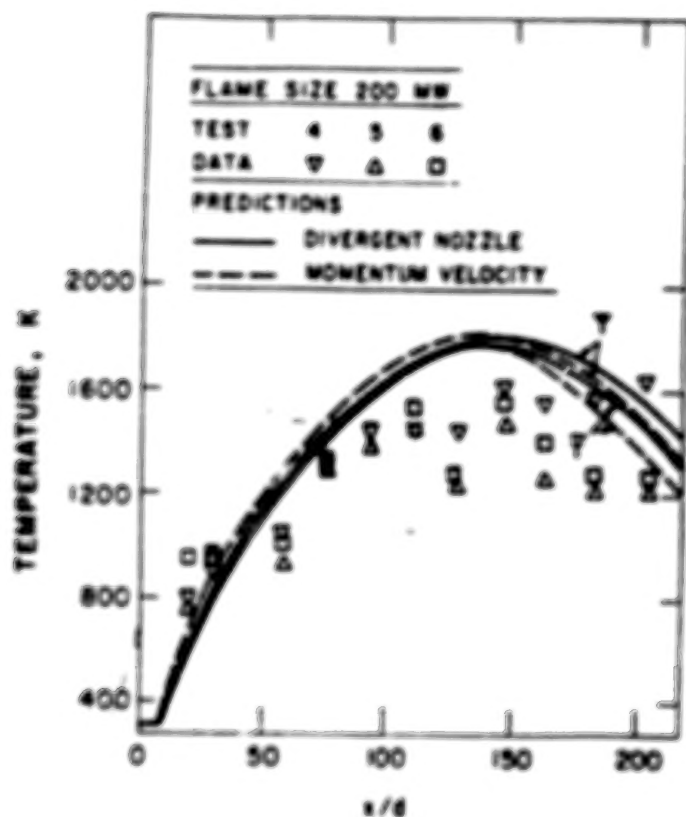


Figure 1 — Measured and Predicted Mean Temperatures Along the Axis of 200 MW Jet-Flame.

Table 1 — Measured and Predicted Radiation Heat Fluxes (kW/m²) from 200 MW Commercial Grade Methane Jet-Flames.

	DETECTOR				
	1	2	3	4	5
TEST #					
4	6.11	10.39	5.68	5.68	6.97
5	5.11	8.29	4.99	5.77	7.08
6	5.61	7.24	4.34	5.24	6.61
MEAN	5.61	8.64	5.00	5.56	6.89
STD DEV.	0.50	1.60	0.67	0.28	0.25
PREDICTIONS	5.17	6.82	4.49	6.68	5.24

This work is being expanded to predict the more intense radiation emitted from combined methane gas and crude oil flames. If these calculations are also successful, the radiation mitigating effects of water spray on flame radiation may also be calculated using the same analysis techniques.

Through a research grant to Louisiana State University, additional testing of the water spray blowout suppression concept was completed (Chauvin and Bourgoyne, 1988). The facilities at the Blowout Prevention school in the Department of Petroleum Engineering permitted both fire tests of greater energy release rates, up to 410 MW (35 MMSCF/D) (McClaffrey and Evans, 1986), and evaluation of the effects of obstructions that stabilize the flame. The same gas flow outlet and spray system used in previous tests in Norman, Oklahoma was used in these tests. Figure 2 shows a compilation of the test results in terms of water spray to gas mass flow rate ratio vs. gas flow rate. At relatively large gas flow rates, unobstructed fires were extinguished at a mass flow rate ratio of 2 over the range of fires (20 to 35 MMSCF/D) representing relatively high gas outlet velocities. This supports earlier measurements made at Norman, Oklahoma and provides some support to extension of results to even larger fires representing actual gas-well blowouts. At lower gas flow rates increasing ratios of water to gas were needed to extinguish the fire. This reflects the poor mixing and spray break-up in the relatively lower velocity gas jet.

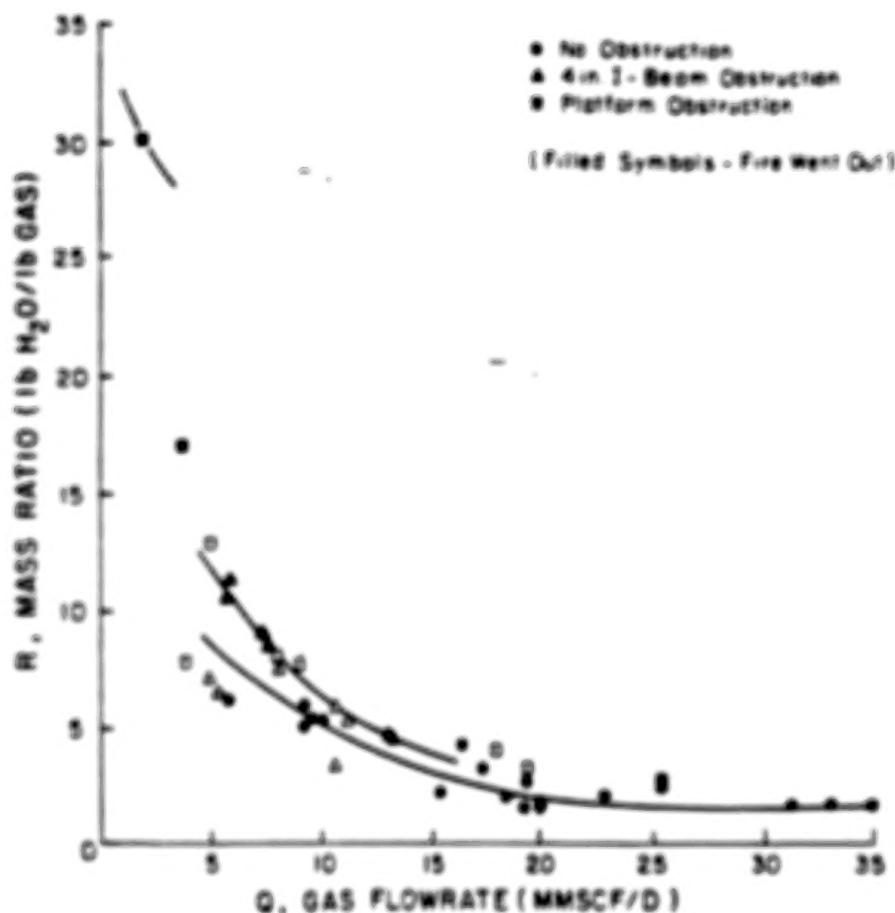


Figure 2 — Water Spray Extinction of Obstructed and Unobstructed Large-Scale Simulated Gas-Well Blowout Fires.

The effect of any obstruction in the gas flow is to increase the ratio of water to gas needed to extinguish the fire. The process of extinction also becomes more erratic as seen by the filled symbols (representing fire extinction) immediately adjacent to open symbols (representing sustained burning). In the case of the broad platform obstruction, fire extinction required mass flow rate ratios greater than fifteen.

It has been seen in smaller scale testing at NBS that even though extinction is more difficult with obstructions in the flame, the increased stability of the obstructed flame allowed greater reduction in the flame radiation through reduced emissions and water spray shielding.

Data have been collected at NBS on the effects of water spray on combined gas and liquid hydrocarbon flames. Tests with total energy release rates of 20 MW, half from methane and half from heptane, have shown that the fires containing liquid fuel are more difficult to extinguish with water spray than pure gas fires having the same total energy release rate. The combustion of the liquid fuel produces a highly radiative flame. Water sprayed into the heptane-methane jet flame can reduce radiation from the flame to one-quarter of its initial intensity. Experiments are being continued to assess the effects of water spray on combined crude oil and methane simulated well blowout fires.



Figure 3 — Twenty Megawatt Combined Heptane-Methane Simulated Blowout Fire at NBS Test Facility.

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Combustion of Oil Spills on Water

Principal Investigator: Dr. David D. Evans
Center for Fire Research
National Bureau of Standards
Gaithersburg, MD 20899

Objective: To characterize the physics of oil spill combustion on open water and in broken ice fields.

In 1985, the Center for Fire Research (CFR) at the U.S. National Bureau of Standards (NBS) began studies of oil spill combustion. This work seeks to quantify the processes involved in oil spill combustion on open waters and in water filled channels formed in broken ice including measurements of smoke production and prediction of smoke dispersal.

The long range goal of the research program is to provide measurements and means to make quantitative predictions of the fraction of oil in a spill that can be consumed by an in-situ combustion process, the characteristics of the residual oil, and the characteristics of the combustion product flow from the burning oil. It is hoped that this information may be cast into a form that is usable by local officials and oil spill response professionals as part of the decision making process in the event of an oil spill.

Previous results from experiments in which crude oil was burned in 0.6 m diameter oil pool fires included measurements of burning rate, thermal radiation emission, smoke production and the chemical composition of both the oil and the burn residue (Evans and others, 1986). Calculations were performed to estimate the surface wind velocities that could be generated by multiple fires distributed over a large area as might be expected during the burning of an oil pool confined by broken ice in the arctic.

This effort is the first in a two year program to quantify the thermal properties and burning characteristics of the crude oil, the physical and chemical properties of the smoke generated in the combustion process, and the expected dispersal of the soot through the atmosphere and deposition downwind of the oil fires. This report summarizes results from these three main research thrusts, all of which are incomplete at this time.

Crude oil burn tests were conducted in the CFR large-scale test building. Details of the experimental apparatus for 0.6 m diameter pool fires with gas analysis and soot sampling are recorded in a previous report (Evans and others, 1986). Larger test burns were conducted in a new 1.2 m diameter pan installed under a calorimeter hood. Instrumentation for the larger burns provided for the measurement of flame temperature, oil and water temperature, energy release rate, radiation feedback from the flames to the liquid surface, and radiation from the flames to the surrounding. Placement of this instrumentation is shown in Figure 1. The energy release rates of the fires burned under this hood are determined using the oxygen consumption calorimeter technique. The energy release rate is calculated from measured decreases in oxygen concentration in the total flow of gases through the stack (Huggett, 1980).

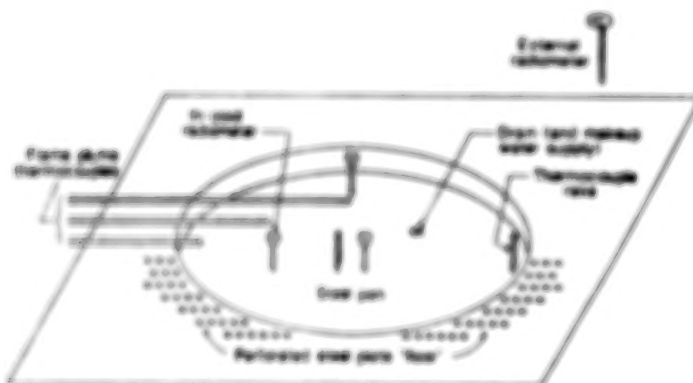


Figure 1 — Diagram of 1.2 m Diameter Pool Fire Apparatus.

The burning characteristics of three types of crude oils were investigated in the large calorimeter — Alberta Sweet, La Rosa and Murban. According to available oil property information (Bohra and Chung, 1986), these oils differ in composition, notably in the percent of the heavier wax plus asphaltene fractions, with Alberta Sweet crude being the lowest and La Rosa crude being the highest.

Important thermal characteristics of the crude oils used in this study are being measured. The thermal conductivity of each oil was measured using the transient hot-wire method (Healy and others, 1982). In this method the thermal conductivity of the liquid is determined by comparing the measured time dependent temperature change of a wire submerged in the liquid reservoir at known initial temperature with the known analytic solution. The thermal conductivity of the three crude oils over the temperature range 0°C to 50°C were constant and nearly equal. Murban and Alberta Sweet have a thermal conductivity of 0.12 W/mK. The thermal conductivity of La Rosa is slightly higher at 0.13 W/mK.

The burning characteristics of the three crude oils were measured in burns under the large calorimeter hood. The use of a 1.2 m diameter pan permitted controlled burning experiments to be conducted under conditions representative of the radiation-dominated, turbulent flow regime of larger pool fires. Each oil was studied at four initial layer thicknesses — 2 mm, 5 mm, 10 mm, and 25 mm. The energy release rate for the Murban crude exhibited an approach to steady-state for the 10 mm and 25 mm layer thicknesses prior to reaching a peak value during the vigorous burning period (see Figure 2). The quasi-steady-state energy release rate for the Murban crude was approximately 0.95 MW (840 kW/m²), actually decreasing noticeably prior to the rapid increase in burning corresponding to a peak level of 2.1 MW (1860 kW/m²) just before burnout. The decrease in energy release rate during the steady burning phase (100 to 500) seconds appears to be associated with the changing composition of the crude oil towards the heavier fractions. The corresponding values of steady-state and peak energy release rates for the Alberta Sweet crude were 1.1 MW (1000 kW/m²) and 2.7 MW (2400 kW/m²). These values are significantly greater than the area specific energy release rate for Alberta Sweet crude (720 kW/m²) measured in the smaller 0.6 m diameter pan fire used for soot measurements. The peak energy release rate for the La Rosa crude was approximately 50% greater than for the Murban crude.

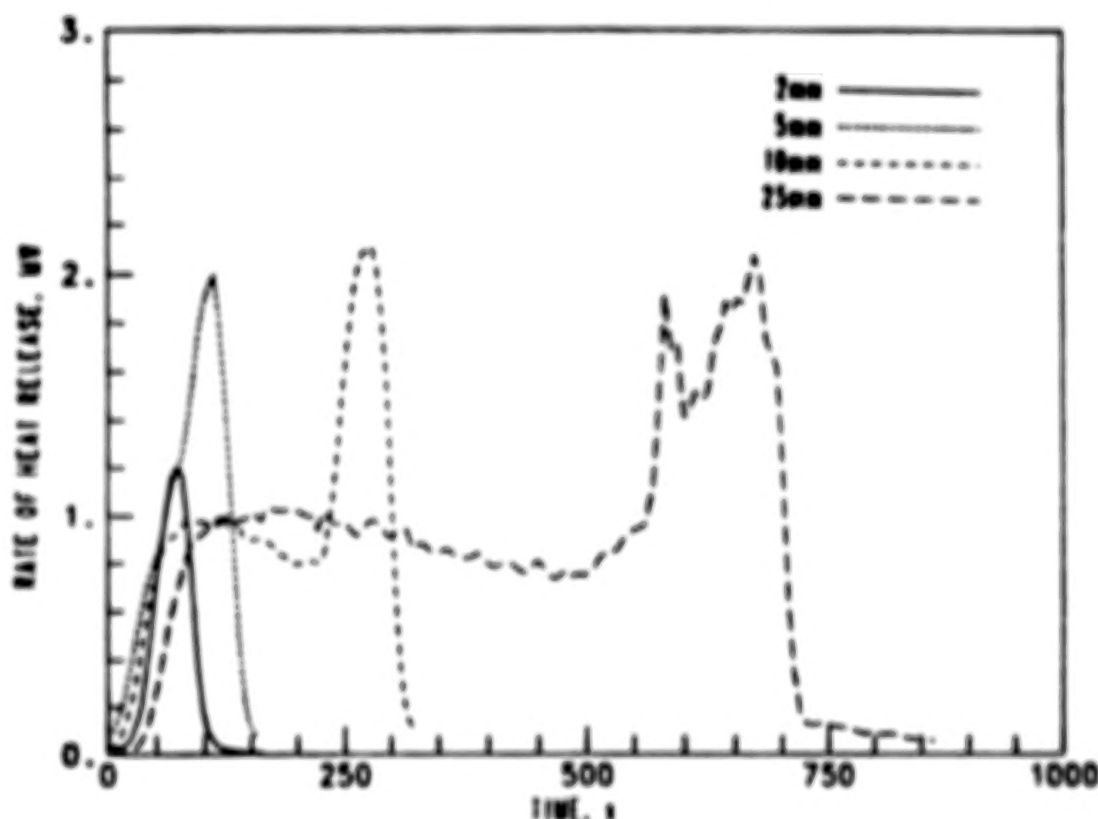


Figure 2 — Energy Release Rate History for 1.2 m Diameter Murban Crude Oil Pool Fires with Differing Initial Layer Thicknesses.

The oil residue remaining following burnout varied with the type of oil and the layer thickness. With one exception, more oil remained from the thickest (25 mm) layer of each oil and slightly more residue remained with the La Rosa crude than with the other oils. The measured residue for all tests ranged from 0.6 kg to 1.2 kg corresponding to a layer depth of approximately 0.6 mm to 1.2 mm.

The chemical characterization of the smoke produced by burning crude oil is important data for total evaluation of the effects of oil spill combustion. Measurements in this study included the organic versus elemental carbon in the smoke, the quantity of selected polynuclear aromatic (PAH) compounds in the smoke, and the amount of CO_2 , CO, NO, and NO_x emitted. Much of the analysis effort was concentrated on the PAH analysis. These PAH compounds are of environmental concern, because some have been reported to be carcinogenic to animals (Boydland, 1981). The results of the PAH analysis are compared with the PAH content of the original crude oil.

In all tests in this series, Alberta Sweet crude oil was burned in a 0.6 m diameter pool. Approximately 9 liters of crude oil were burned in each test, which corresponded to a fuel depth of about 30 mm. The sample burning time was found to be about fifteen minutes. Smoke samples were collected on filters heated to match the stack temperature, about 100°C, using a heated transfer line ("H" series tests). The smoke sample was collected during the time of visually steady burning. Smoke samples were also collected and diluted before collection on filters with air cooled to about 10°C to simulate the cooling that would naturally occur in a rising smoke plume ("C" series tests). In all tests two samples (sample 1 before sample 2) were collected on the filters before the rapid burning period.

The results of the smoke emission measurements are contained in Table 1. The smoke yield, e , which is defined as the mass of smoke aerosol generated per mass of fuel consumed, is found to have a value of about 0.10. This is similar to the value found in previous tests with Prudhoe Bay crude oil (Evans and others, 1986). The value of e increases in going from sample 1 to sample 2 indicating that the smoke emission increases as the fuel presumably distills leaving the sootier component for the later stage of burning.

Table 1 — Summary of Smoke Emission Data for 60 cm Diameter Alberta Sweet Crude Oil Pool Fires.

Parameters	Test H-1 Sample 1	Test H-1 Sample 2	Test H-4 Sample 1	Test H-4 Sample 2	AVERAGE
dQ/dt , kW	217	172	234	191	204
dm/dt , g/s	5.27	4.40	5.43	4.93	5.04
R , KJ/g	37.4	39.8	41.7	38.8	39.4
e_1	0.076	0.119	0.100	0.110	0.101
e_2	0.070	0.110	0.09	0.101	0.093
Parameters	Test C-3	Test C-7	AVERAGE		
dQ/dt , kW	205	203	204		
dm/dt , g/s	4.98	5.57	5.28		
R , KJ/g	41.1	36.3	38.7		
e_1	0.087	0.079	0.083		
e_2	0.080	0.079	0.080		

Legend

H-1 and H-4 refer to identical crude oil burns in which the filter collection system was heated to about 100 °C.
 C-3 and C-7 refer to identical crude oil burns in which the smoke is cooled to ambient temperature in a sampling dilution system.
 dQ/dt - heat release rate of the fuel
 dm/dt - burning rate of the fuel
 R - heat of combustion
 e_1 and e_2 refer to the smoke yield based on a flux method and a carbon balance method [1], respectively.

The smoke collected in tests C-5 and C-7 was first diluted and thus cooled by the stack sampling probe. The mass flow of ice cooled dilution air is approximately twice the mass flow of the air sampled from the stack. The manifold temperature just prior to the filter is observed to be within 2 °C of the ambient temperature. The value of e obtained under these conditions is 15 percent to 20 percent less than the value obtained for the heated, undiluted sample. Normally, one would expect an increase in e with dilution by cool air resulting from the condensation of organic vapors. The PAH analysis discussed below clearly shows that the higher vapor pressure PAH's are greatly enriched in the diluted sample compared to the high temperature sample. The observed decrease in these tests may be the result of smoke deposition by thermophoresis in the entrance portion of the diluter and by turbulent flow in the mixing region of the diluter.

The emission of CO, CO₂, NO, and NO₂ was monitored during selected tests. The concentrations of CO and CO₂ were measured by standard gas analysis instrumentation based on nondispersive infrared spectroscopy. The smoke aerosol was filtered and the moisture condensed out with a dry ice trap before the sampled gas entered the CO and CO₂ analyzers. The analysis of the nitrogen oxides is based on the reaction of ozone with the oxides and detection of the resulting chemiluminescence with a photocell. The CO₂ accounts for over 95% of the gaseous products measured as indicated in Table 2. The other principal product of combustion, H₂O, was not measured. The volume fractions of CO, NO, and NO₂ relative to CO₂ were found to be about 0.038, 1.5×10^{-4} , and 4×10^{-4} , respectively. The concentrations of NO and NO₂ were just above the detection threshold.

Table 2 — Gaseous Emission from Alberta Sweet Crude Oil

Species	C-6 ppm	C-7 ppm	C-6 fract.*	C-7 fract.*
CO ₂	4604	4906		
CO	174	187	0.038	0.038
NO	0.7	0.7	1.6×10^{-4}	1.5×10^{-4}
NO ₂	2.3	1.7	5.0×10^{-4}	4.0×10^{-4}

.....

* Volume fraction of gas species relative to CO₂.

Smoke aerosol produced by flaming combustion is composed of a graphitic or so called elemental carbon fraction and an organic carbon fraction. Smoke samples were collected on quartz fiber filters and sent to a contract laboratory for thermal-optical analysis for organic/elemental carbon (Johnson and others, 1981). The elemental carbon content of the smoke was found to be over 90%.

Eight smoke samples weighing 10 mg to 15 mg each were deposited on teflon filters and were analyzed for 15 polynuclear aromatic hydrocarbons (PAHs) using combined liquid and gas chromatographic techniques. Wise and Benner from the Center for Analytical Chemistry (NBS) performed the analysis on four of the samples by a method previously used by them in quantifying the PAH content of two standard reference air particulate samples (Wise and others, 1986). The PAH concentration in the smoke for samples similar to those analyzed at NBS were analyzed at the laboratories of Environment Canada in Ottawa. Capillary gas chromatography with flame ionization detection (GC-FID) was used at NBS for the measurement of 15 PAHs in the four filter extracts. The PAHs were determined by comparison of peak areas of the analytes with those of the internal standards. The names and structures of PAHs for selected peaks in the chromatogram are given in Figure 3.

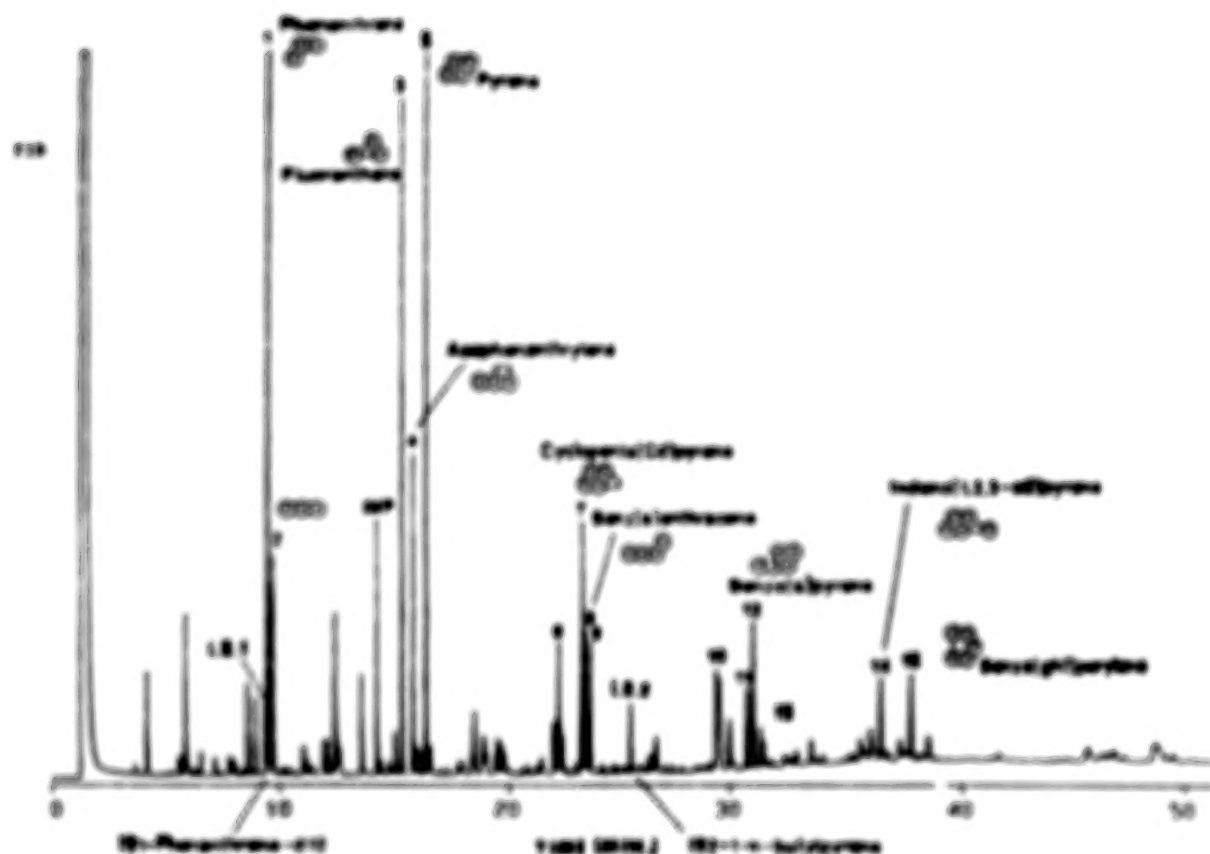


Figure 3 — Gas Chromatogram of Smoke Sample Collected at Ambient Temperature (C-5, #1).

It is known that the crude oil fuels themselves have a PAH component. Overall, for the compounds measured, the total PAH fraction of the smoke and the original oil burned are nearly equal. It is also of interest to compare the amount of selected PAHs per gram of fuel versus the amounts of PAHs collected in the smoke per gram of fuel consumed. As seen in Table 3, the relative concentration of the individual PAH compounds is different in the fuel compared to the smoke. For example, the concentration of phenanthrene plus anthracene in the fuel (296 mg/g) is about 2 times greater than for the smoke (133 mg/g fuel burned), while the concentration of benzo(a)pyrene (BaP) is a factor of three lower for the fuel (3 mg/g) compared to the smoke (18 mg/g). This indicates that the combustion process itself is generating specific PAHs and that the PAH content of the fuel will not represent the distribution of PAHs emitted. There is about a four-fold enrichment of the four-six ring PAHs in the smoke compared to the crude oil.

BaP has been used as a surrogate for the overall carcinogenic effect of PAHs. The higher BaP concentration in the smoke relative to the fuel is of environmental concern; however, two key issues must be addressed before a full assessment of PAH emission can be made. The effect of burning rate on PAH emission should be analyzed. Smoke was not collected during the very rapid burning stage near the end of a test, but this burning phase may be dominant in a large fire with a thin oil layer. An analysis of the vapor phase PAHs should be made to complete the present analysis that has concentrated on condensed phase products.

The object of this fire plume analysis is to develop a methodology which will permit the prediction of smoke dispersal generated by one or more oil spill fires in close proximity. In order to allow for the possibility of large composite fires, there are three main ingredients that must be taken into account in the analysis. They are the stratification of the atmosphere, ambient winds, and the properties of the initial fire plume. The scale of the phenomena to be considered is roughly 1-3 kilometers in the vertical (the plume rise height), a comparable spread laterally in a direction perpendicular to the ambient wind, and anywhere from 20 to 200 kilometers in the downwind direction.

Table 3 — Comparison of PAH Content of Alberta Sweet Crude Oil and Smoke from Burned Oil.

No. ^a	PAH	Crude Oil mg/l ^b	Smoke mg/l ^c
	Acenaphthylene	61	
	Acenaphthene	6.5	
	Fluorene	100	
1	Phenanthrene	190 ^d	100
2	Anthracene		20
3	Fluoranthene	22	70
4	Acenaphthenylene		40
5	Pyrene	21	60
6	Benz[a]ghi- fluoranthene		22
7	Pyro[1,2,3-cd] pyrene		50
8	Benz[a]anthracene	6.5	22
9	Chrysene/ benzophenylene	10	25
10	Benz[b,j,k] fluoranthene	6.5	30
11	Benz[k]pyrene	21	32
12	Benz[a]pyrene	5	18
13	Benzo[e]pyrene	6.5	0
14	Indeno[1,2,3-cd] pyrene	6.5	20
15	Benz[ghi]perylene	6.5	21
Total conc. of PAHs		100	100

^a PAH identification numbers for Figure 1.

^b mg/kg crude oil. Analysis performed by Environment Canada.

^c mg/kg of crude oil burned causing smoke emission factor $\times 10^3$ of 0.30.

^d mg/kg crude oil. Analysis performed by EDC.

^e This number represents the sum of phenanthrene and anthracene.

Given the scale of these plumes, the Reynolds or Grashof numbers of the associated flow patterns are enormous, and a description which omits molecular diffusion of mass, momentum and energy is reasonable. The transport of smoke aerosol, the object of primary interest, is dominated by large scale advection. We are not concerned with the initial establishment of the plumes, so that a steady state picture of the dispersal process is appropriate. Under these circumstances the equations expressing the conservation of mass, momentum, and energy in the flow were formulated and solved using the ideal gas equation of state and initial fire plume velocity and temperature correlations (McCaffrey, 1983). In these solutions the ambient wind is assumed to vary with height but flow in a constant direction. The calculations are begun at an altitude sufficiently low so that the wind has not yet had much of an effect on the plume, and distinct fire plumes have not yet merged. For individual fires in the range 100-1000 MW, this altitude should typically be in the range 50-150 M.

This problem is close to one solved previously (Baum and others, 1982). The problem to be solved is now explicitly two dimensional and time dependent with suitably scaled distance downwind playing the role of time. There are two significant differences, which will require modifications to earlier calculations before quantitative predictions can be made. First, the ambient stratification of temperature and density appear in the equations to be solved in a fundamental way. Second, the enclosure walls built into the calculations (Baum and others, 1982) must be removed. Still, the equations are close enough that it is worthwhile to see the kind of results which emerge from a related enclosure fire computation.

To make use of the previous computer programs for demonstration of the capabilities of this type of analysis, the problem of a "thermal" generated in the enclosure was calculated. Figure 4 shows (potential) temperature contours shortly after the heat pulse representing the oil fire is turned on. The frame of reference is now a plane sweeping downstream with the ambient wind velocity. Figure 5 shows the plume just downwind of the fire. It is now bent over and barely connected to the "ground". Figure 6

shows the initial development of the typical counter-rotating vortex pair in the plume as it rises above the datum level much further downstream. Finally, in Figure 7 the vortex structure is quite pronounced. The plume structure this distance downstream would probably be strongly modified by stratification and the presence of plumes generated by other fires. Some indication of the latter effect might be inferred by considering this sequence to represent an infinite periodic array of plumes aligned perpendicular to the wind. However, definitive answers can only come from calculations based on a full analysis with appropriate boundary conditions (Evans, et al., 1988). Future work will focus on this problem.



Figure 4 — Temperature Contours at Front of Wind Blown Plume Using Transient Enclosure Flow Analogy.

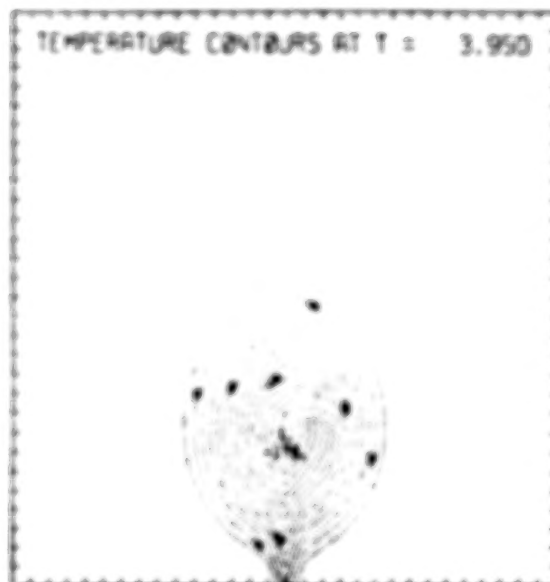


Figure 5 — Temperature Contours Just Downwind of Fire Using Transient Enclosure Flow Analogy.

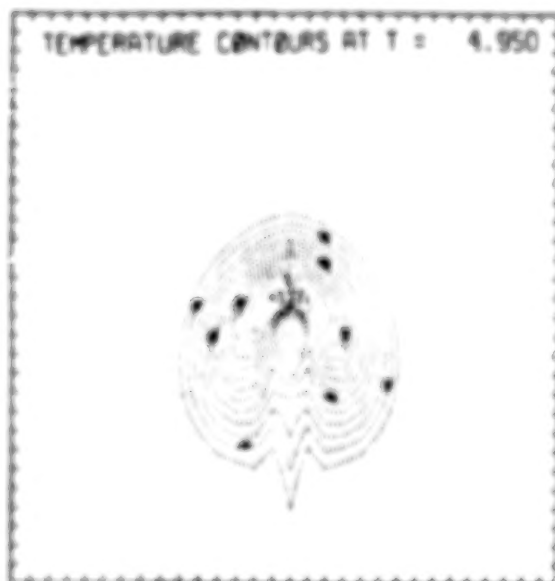


Figure 6 — Temperature Contours at Point of Vortex Pair Formation Using Transient Enclosure Flow Analogy.

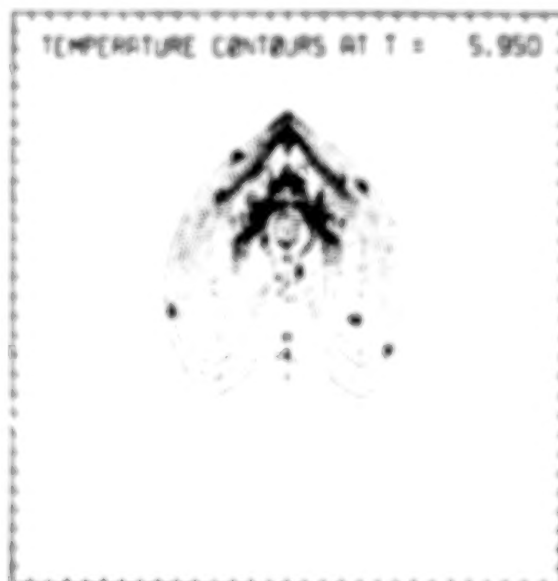


Figure 7 — Far Downwind Temperature Contours Using Transient Enclosure Flow Analogy.

Summary

An experimental facility has been completed to examine the burning conditions of crude oil in a 1.2 m diameter pool fire configuration. This facility permitted controlled burning experiments to be conducted under conditions representative of the radiation-dominated, turbulent flow regime of larger pool fires that might occur on the open ocean or in pools confined by broken ice. Tests with three different crude oils, Alberta Sweet, La Rosa, and Murban were conducted using initial oil depths of 2 mm, 4 mm, 10 mm and 25 mm floated on a deep water layer.

At oil depths of 10 mm and 25 mm each oil exhibited two distinct burning stages. The first was associated with a progressive vaporization of the burning oil layer and the other with more intense, short duration burning in which the oil surface was churned and splattered by boiling water under the thin oil layer. For Murban crude oil, the steady burning resulted in energy release rates of 840 kW/m^2 which increased to 1860 kW/m^2 during the vigorous burning before extinction. Residual oil left on the water surface at the end of natural burning corresponded to a uniform layer depth of 0.6 mm to 1.2 mm.

The burning of Alberta Sweet crude oil results in a high smoke emission with ϵ about 0.10 (10% conversion to smoke). The smoke has a high elemental carbon component in excess of 90% resulting in a highly light absorbing soot.

The primary gaseous product of combustion is CO_2 with the CO concentration about a factor of 25 lower than CO_2 . The emission of NO and NO_x are less than one thousandth the concentration of CO_2 .

Independent analyses of the PAH content of the smoke by the National Bureau of Standards and Environment Canada showed the same trends and had good overall agreement for 12 individual PAHs. The PAH content of the smoke was nearly equal to that in the original oil burned. The PAH content of the smoke was enriched in the larger species in comparison with the fuel. The concentration of benzo(a)pyrene, which is often used as a surrogate for the carcinogenic effect of PAH, was found to be three times greater in the crude oil smoke per gram of fuel consumed compared to the crude oil itself. The concentrations of the three ring PAHs were found to be very sensitive to the filter collection temperature. Thus, it is important to use a diluter when sampling the PAHs to simulate the conditions existing in a rising smoke plume.

An analysis of the dispersal of fire plumes by atmospheric winds was presented. It was demonstrated that as the plume buoyancy weakens with altitude and plume gets bent over by ambient winds, the equations describing the dispersal process are greatly simplified. Physically, they are equivalent to studying the two-dimensional but time dependent process by which a buoyant thermal equilibrates with a stratified atmosphere at rest. Sample results of a similar process occurring inside an enclosure have been shown. This approximate model can be used to calculate realistic dispersion of oil spill combustion generated smoke with moderate sized computing resources.

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